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Review

In-Line Inspection (ILI) Techniques for Subsea Pipelines: State-of-the-Art

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Abstract: Offshore oil and gas resources play a crucial role in supplementing the energy needs of human society. The crisscrossing subsea pipeline network, which serves as vital infrastructure for the storage and transportation of offshore oil and gas, requires regular inspection and maintenance to ensure safe operation and prevent ecological pollution. In-line inspection (ILI) techniques have been widely used in the detection and inspection of potential hazards within the pipeline network. This paper offers an overview of ILI techniques used in subsea pipelines, examining their advantages, limitations, applicable scenarios, and performance. It aims to provide valuable insights for the selection of ILI technologies in engineering and may be beneficial for those involved in pipeline integrity management and planning.

Keywords: subsea pipelines; in-line inspection (ILI); non-destructive testing (NDT); pipeline inspection gauge (PIG)

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1. Introduction

The ocean, teeming with an array of resources such as oil and gas reserves, mineral deposits, diverse biological entities, and vital water reserves, is often hailed as the "blue frontier" [1–5]. Subsea energy minerals within the oceanic strata, due to their immense economic value, have been extensively exploited [6,7]. Taking offshore oil and gas resources as an example, with the rapid development of ocean engineering technology [8–10], the cost and difficulty of production have been decreasing year by year [11,12]. In addition, the geopolitical influence and the increasing cost of onshore oil and gas extraction have made offshore energy an important growth area for energy supply [13–16]. Consequently, there is an urgent societal and economic demand for rapid, voluminous, economical, and reliable oil and gas storage and transportation [17].

Subsea pipelines offer a definitive solution [18–21]. Originating in the Gulf of Mexico in the United States, the world's first subsea pipeline was constructed there in 1951, spanning a total length of 16 kilometers. As depicted in Figure 1, subsequent to this milestone, the global construction of subsea pipelines expanded comprehensively, encompassing regions such as North America, Latin America, Australasia, East Asia, Southeast Asia, Africa, the Mediterranean, and the Middle East [22]. This has led to the formation of a vast and interconnected network of undersea pipelines. Compared to maritime shipping, subsea pipelines have saved substantial costs in cross-sea oil product transportation, achieving notable economic and scale benefits [23]. Taking China as an example, pipelines, which constitute 5% of the total length of subsea oil and gas pipelines, handle 25% of the total throughput of petroleum and natural gas [24].

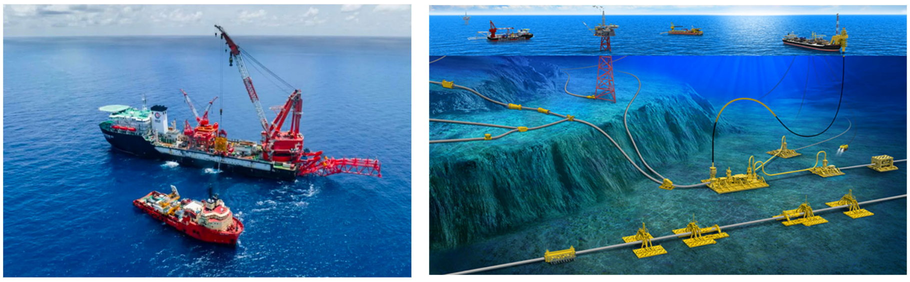

Figure 1. Laying of subsea pipelines (**left**) and a crisscrossing subsea pipeline network (**right**).

However, corresponding to this, the maintenance cost of subsea pipelines is also extremely high [25]. Subsea pipelines may suffer from deformation defects under various damaging factors (such as corrosion, alternating sea currents, geological deformation, and human activities) [26–28]. Severe interplay among these factors can exacerbate each other and may even lead to pipeline rupture, causing major safety accidents, and inestimable damage to the global environment and regional economies [29,30]. As shown in Figure 2, the oil spill from the 2010 Gulf of Mexico oil drilling platform was considered the worst marine oil spill in American history, causing massive ecological devastation [31] and sparking subsequent studies on the aftermath of this event by numerous scholars [32–35]. In 2022, explosions occurred in the primary pipelines transporting natural gas from Russia to Europe, the Nord Stream 1 and Nord Stream 2, severely affecting the energy supply in Europe, exacerbating the European energy crisis, and impacting regional politics [36]. As the lifeline of offshore oil and gas engineering [37], maintaining the integrity of pipelines becomes an area of increasing relevance [38]

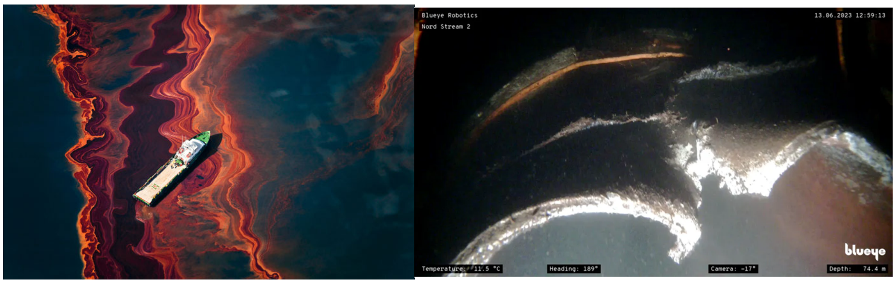

Figure 2. Oil spill in the Gulf of Mexico (**left**) and damaged section of the Nord Stream pipeline (**right**).

The length of submarine pipelines is generally measured in kilometers, and the length of some longer submarine pipelines can reach tens of kilometers, making it quite difficult to inspect for damage. For submarine pipelines that have already leaked, remote sensing, the negative pressure wave method, the subsonic wave method, and the Transient Test-Based Techniques (TTBTs) can be used for leak detection and localization [39,40]. Taking negative pressure waves and TTBTs as examples, data quality, a dynamic slope in anomaly detection, and false alarms caused by normal working condition changes are the three primary technological challenges associated with the negative pressure wave [41]. Furthermore, achieving an accurate estimation of the time difference between the arrival of leakage-induced negative pressure wave signals at the sensor's two sides is key in precisely locating the leakage point. In this regard, a leakage location algorithm based on difference cross-correlation delay estimation has been established [42]. TTBTs can offer the capability to detect not only leaks but also various defects, such as partial blockages, wall deterioration, and even branching features. Moreover, TTBTs have proven their effectiveness not only in controlled laboratory environments but also under real-world conditions in operational pipe systems [43–45]. For pipelines that have not yet leaked, their daily maintenance relies on monitoring the operating parameters of the pipeline system (such as the pressure, temperature, flow rate, density, and pH value at the inlet and outlet), checking fluid composition data, inspecting cleaning data, and inspecting corrosion monitoring data [46]. For suspected deformation points, in-line inspection (ILI) is accepted as the optimum approach, detecting and qualifying flaws as well as revealing the growth rate information of active flaws [47,48].

The typical underwater pipeline inspection process includes pigging, flushing, mechanical cleaning, internal inspection, and issuing an inspection report. The narrow sense of pipeline internal inspection specifically refers to the measurement and evaluation of parameters such as pipeline deformation defects, metal loss, cracks, welds, and structural dimensions. This is the scope of the discussion in this article.

Figure 3 depicts the classification of ILI methodologies, including geometry deformation mapping (DEF) and NDT methods. These NDT techniques cover a wide array of technologies, typically including Magnetic Flux Leakage (MFL), Ultrasonic Testing (UT), Eddy Current Testing (ECT), Electromagnetic Acoustic Testing (EMAT), and Acoustic Resonance Technology (ART).

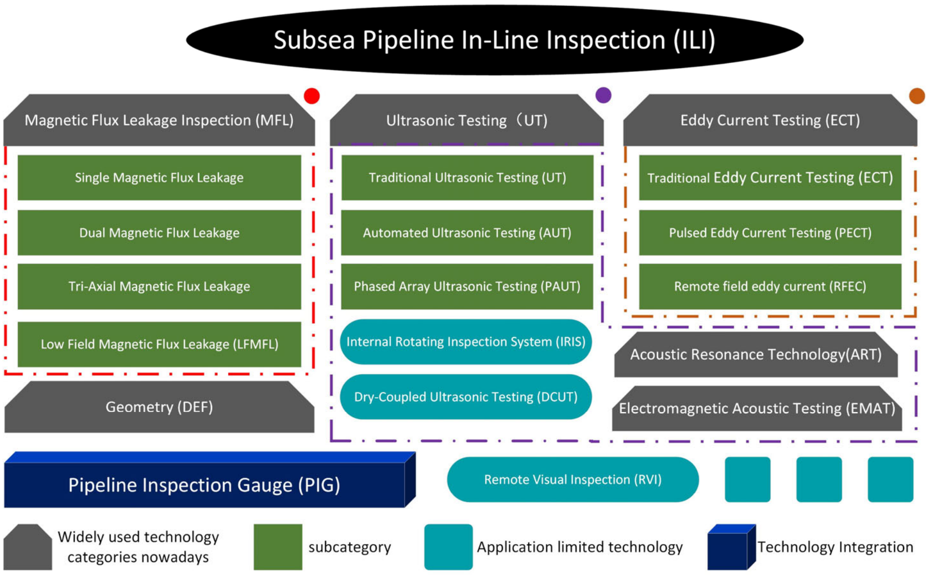

Figure 3. Classification of internal inspection techniques for submarine pipelines.

The solitary application of each technology can lead to partial insights into pipeline health due to their individual constraints. However, integrating these NDT methods within a single Pipeline Inspection Gauge (PIG) framework allows for a comprehensive, multi-faceted analysis. Such an integrated approach enables the cross-verification of data, enhancing detection accuracy and reliability. This consensus for a united inspection system has evolved from the necessity to ensure maximal coverage and diagnostic precision, facilitating preemptive maintenance strategies and reducing the risk of pipeline failures.

2. Existing Commonly Used ILI Technologies

As previously indicated, each ILI technology exhibits distinct advantages as well as corresponding limitations. The forthcoming sections will concisely delve into the operational principles of these technologies, analyzing their practical implementations as well as the challenges they face in the context of submarine pipeline inspections. The discourse will also encompass an overview of leading manufacturers, their innovative products, and significant contributions to research, providing an in-depth perspective of the latest developments in this domain.

2.1. Geometry Deformation Mapping (DEF)

The ILI DEF tool, as shown in Figure 4, comes with a comprehensive set of calipers designed to improve the detection and accurate assessment of variations in the internal diameter of pipelines. The sensors are meticulously arranged to achieve extensive coverage, ensuring the reliable detection and measurement of pipeline changes, including bends, buckles, dents, and wrinkles, and generating a deformation cloud diagram for comprehensive analysis.

Figure 4. ILI geometry deformation mapping tool from ROSEN and deformation cloud diagram.

Mechanical contact mapping employs tactile sensors that scan the wall surface of the pipeline, documenting surface anomalies that may be indicative of dents, corrosion, or other damage. Although this method offers direct contact measurement, it is constrained by the potential for damaging the pipeline's coating and a reduced ability to detect minor defects. To overcome these limitations, electromagnetic proximity sensors have been introduced. These sensors function without needing to make direct contact with the pipe wall. Using eddy current technology, EM sensors are mounted on a ring sized to clear the minimum anticipated internal diameter of the pipeline, allowing them to gauge the gap between the sensor ring and the pipe wall. Nonetheless, given their non-contact nature, the precision of these sensors depends on regular calibration to ensure accuracy. Thus, integrating both technologies helps to mitigate their individual limitations, providing a more reliable measurement system. As shown in Figure 5, three distinct mapping methodologies have emerged: Direct Arm Measurement Caliper Angle or Movement Sensor (DAMC), Indirect EM Caliper (IEMC), and Direct Arm Measurement Caliper Angle or Movement Sensor with Electromagnetic Proximity Sensors (DAMC + IEMC) [49].

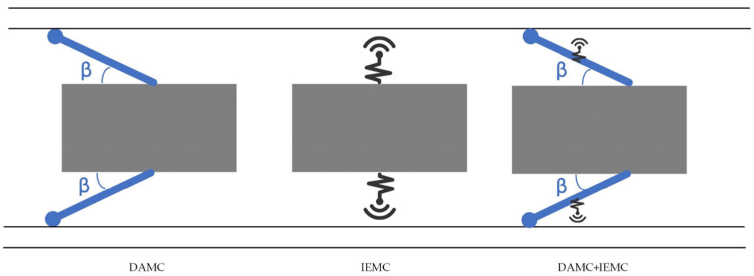

Figure 5. Types of ILI geometry deformation mapping calipers.

DEF is a reliable technology for gathering comprehensive data on the integrity of both liquid and gas pipelines. This technology offers full circumferential and axial coverage, which is critical for assessing the condition of a pipeline with high fidelity. One of the key advantages of mechanical caliper tools is their ability to distinguish between actual geometric irregularities and other non-structural features such as debris, scale, or wax deposits. This capability significantly reduces the likelihood of false positives, enhancing the overall reliability of the inspection process.

DEF tools are typically incorporated within PIGs, where they serve a crucial function by accurately charting pipeline deformations—identifying ovalities, dents, buckles, and bends—and upholding pipeline integrity [50]. With a focus on reducing friction and maintaining a lightweight design, mechanical caliper tools are crafted to yield accurate data under both low and high operational pressures. Another critical design goal is to minimize resistance and the required force to propel the tool as it traverses the pipeline. Typically, the effective operation of a DEF tool also necessitates assistance from internal pipeline navigation to accurately locate defects. Commonly employed methods include odometer wheels, inertial measurement units (IMU) and ultra-low frequency (ULF) electromagnetic wave positioning technology [51–53]. These are utilized to obtain PIG's position information within the pipelines. For complete localization, this is further complemented by matching with sonar positioning and GPS technologies [54].

However, relying solely on the DEF tool does not provide a sufficiently comprehensive dataset for a complete integrity assessment of the pipeline. The common industry approach is to combine this tool with NDT-based inspection tools, which offer more precise and abundant information.

2.2. Magnetic Flux Leakage (MFL)

MFL is currently one of the most widely used NDT techniques for pipeline inspection, first introduced in 1969, and it can effectively detect metal loss, cracks, weld defects, etc. [55,56]. When the MFL tool moves through the pipeline, the magnetic flux generated by the magnet is coupled to the pipe wall through the iron brush, forming a magnetic circuit between the pipe wall and the tool. If there are defects inside the material, the magnetic permeability at the defect will change, causing the path of the magnetic field lines to alter. When the defect size is large or the magnetic induction intensity is high, the magnetic resistance at the defect location will significantly increase, causing the magnetic field lines to leak near the defect, forming a magnetic leakage field [57,58]. The mechanism of the formation of a magnetic leakage field in a defect B_{mfl} can be expressed by the following formula [59]:

$$B_{mfl} = B_r + B_d - B_c \tag{1}$$

where B_r is the magnetic induction intensity caused by magnetic refraction at the defect, B_d is the magnetic induction intensity caused by magnetic diffusion at the defect, and B_c is the magnetic induction intensity caused by magnetic compression at the defect.

The MFL technique is particularly well suited for inspecting pipelines that are in service, as it does not require the removal of coatings or insulation and can effectively detect defects through a wide range of pipe diameters and wall thicknesses. This makes it a cost-effective and efficient method for pipeline inspection, minimizing downtime and disruption to operations. With advancements in technology and data analysis, MFL continues to evolve as an indispensable tool for ensuring the integrity and safety of pipelines, preventing potential leaks, ruptures, or failures.

Due to the fact that magnetic flux leakage is a vector, and sensors can only measure in one direction, a probe containing three sensors is required to accurately measure the axial, radial, and circumferential components of the MFL signal. The traditional single-axis measurement method of MFL results in a poor capability in measuring axial orientation features. For single MFL inspection, if a defect is elongated and its main orientation is aligned with the MFL being detected, the defect will be difficult to detect [60]. The importance of the orientation of the magnetic field for detection is shown in Figure 6. Therefore, dual-axis MFL and Tri-axis MFL have been designed to measure the absolute magnetic field vector and enhance the detection capability for different types of defects, improving the accuracy of defect size measurement [61].

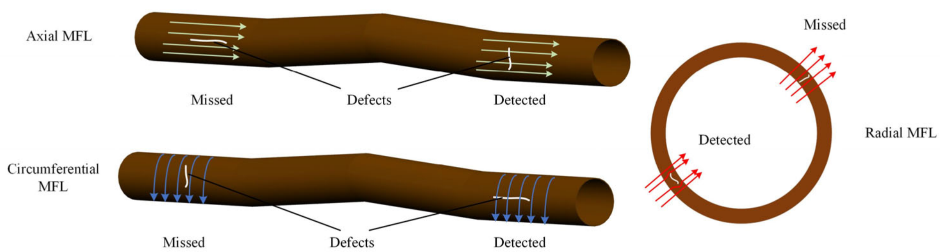

Figure 6. Importance of the orientation of the magnetic field for detection.

As shown in Figure 7, T.D. Williamson (Tulsa, OK, USA), a company with a legacy of over a century, is an esteemed global leader in providing solutions for pressurized piping systems. The company has pioneered various detection methods based on the MFL principle, such as Low Field Magnetic Flux Leakage (LFM), Gas Magnetic Flux Leakage (GMFL), and SpirALL® Magnetic Flux Leakage (SMFL), among others.

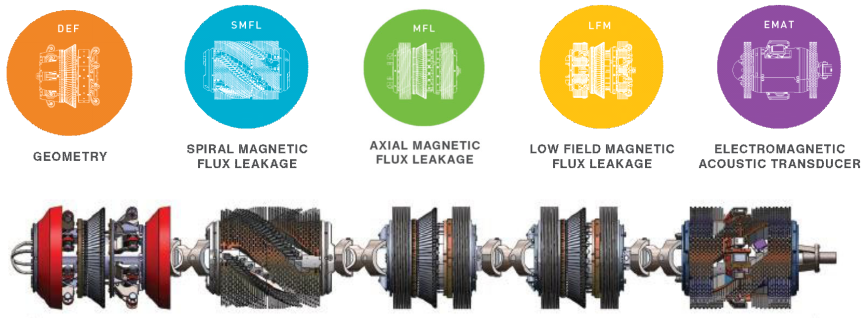

Figure 7. TDW's ILI suite (DEF + SMFL + MFL + LFM + EMAT).

MFL is based on the high magnetic permeability of ferromagnetic materials, so MFL is not effective for non-magnetic materials. In addition, the radial dimensions of pipelines are relatively small, and the measurement effectiveness for thin-walled pipelines is poor. Furthermore, MFL requires high precision, with the testing tool needing to tightly fit the inner wall of the pipeline, so it is also not suitable for complex shapes, pipelines with a high level of internal deposition, and poor flow characteristics [62].

In the domain of Inline Inspection (ILI) utilizing Magnetic Flux Leakage (MFL) technology, the market is indeed dominated by well-established companies from Europe and America, which are renowned for their technological advancements and significant investments in research and development. European companies like ROSEN from Switzerland and 3P Services from Germany have made substantial contributions to the development of MFL technology. ROSEN is known for its wide array of diagnostic tools and advanced data analysis techniques, while 3P Services offers customized solutions for pipeline inspection and has expertise in handling complex inline inspection challenges. The PII company based in Stoke-on-Trent, UK, and NDT Global company located in Dublin, Ireland, both provide a range of services including pipeline inspection, integrity assessment, and the life extension of existing pipeline systems. Their technologies and services are vital in ensuring the safety and efficiency of pipeline operations.

American companies like Baker Hughes, T.D. Williamson, and Emerson (Saint Louis, MO, USA) are giants in the field, with Baker Hughes being notable for its extensive portfolio of inspection tools and advanced sensor technologies. T.D. Williamson has a long history of innovation in pipeline equipment, offering a wide range of services from hot tapping to pipeline integrity management. Emerson is known for its emphasis on digital transformation and smart technologies to enhance pipeline safety and operation.

As for the Asian market, it is rapidly evolving, with companies like Cosmo Engineering from Osaka, Japan, DEXON from Rayong, Thailand, and CNOOC from Beijing, China, making their mark. These companies are contributing to the increasing diversity in the ILI MFL tools market and are expected to bring new perspectives and innovations that could potentially lead to more efficient and cost-effective pipeline inspection solutions. ILI tools utilizing MFL technology are shown in Figures 8 and 9.

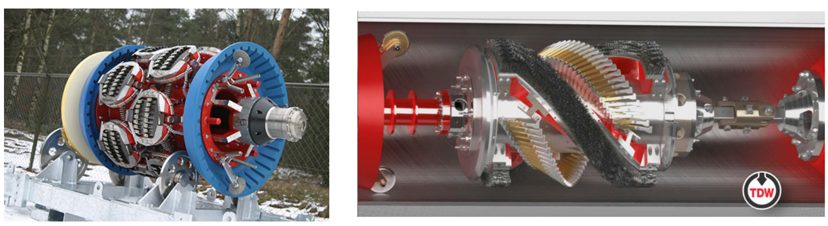

Figure 8. ROSEN's RoCorr MFL-C and TDW's SpirALL® MFL.

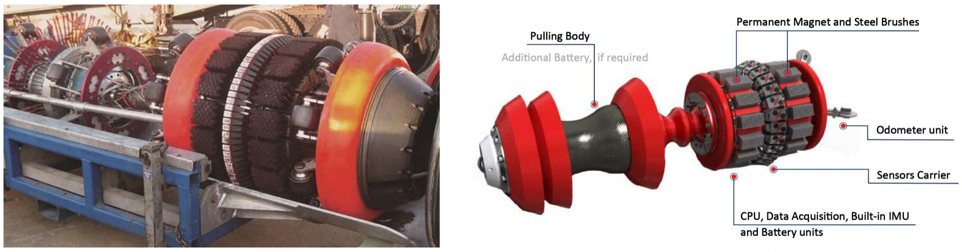

Figure 9. Baker Hughes's MagneScan™ MFL and DEXON's MFL tool.

Taking China as a focal point, CNOOC has demonstrated a long-standing commitment to MFL equipment innovation, with a growing emphasis on indigenous development. Over the years, they have achieved notable advancements in technology, enhancing their competitive edge in the global arena [63–65]. The collaborative effort between China Aerospace Science and Industry Corporation (CASIC), based in Beijing, China, and CNOOC, also headquartered in Beijing, China, has resulted in a self-developed MFL detector that is poised to dramatically reduce the cost of submarine pipeline inspection by 30–50%. This breakthrough is expected to yield annual cost savings of at least CNY 80 million (over USD 12 million) [66].

Research on MFL has been continually advancing since 1969. S. Kathirmani et al. proposed a three-level algorithm that achieves a high compression ratio with a low normalized mean square error (NMSE) and considerable robustness to a baseline shift [67]. Jian Feng et al. developed a harmful and non-harmful defect recognition method based on MFL images using a convolutional neural network (CNN), bypassing the feature extraction process [58]. They also constructed an enhancement module and significantly improved the average precision and recognition accuracy through task-oriented joint training with a new loss function [68]. Lin Jiang et al. proposed a weak defect detection method for MFL based on a two-stage heterogeneous signals mutual supervision network (THMS-Net) [69]. Cui Guoning from Shenyang University of Technology utilized a deep convolutional neural network to quantitatively analyze the structured data of the MFL detection signal at the pipeline defect, extracting the features of MFL detection data at the pipeline defect using convolutional kernels to achieve intelligent recognition [70]. Hubert Lindner led an ILI project targeting high-pressure, multi-diameter, and heavy-wall subsea pipelines. To tackle challenges associated with conventionally unpiggable pipelines, especially offshore ones with diverse diameters, Lindner collaborated with ROSEN to develop and test a PIG based on two ILI tools: geometry and MFL. Through meticulous planning and effective teamwork, these tools underwent design improvements, ultimately delivering precise and high-quality data [71].

2.3. Ultrasonic Testing (UT)

Ultrasonic Testing (UT) is another widely used technology for in-pipe inspections [53]. Ultrasonics refer to mechanical waves that propagate through an elastic medium with frequencies above 20 kHz, characterized by excellent directionality, strong penetration capabilities, and high energy. Additionally, material properties such as the sound velocity, attenuation, and acoustic impedance carry rich information, which forms the basis of the widespread application of ultrasonics. Ultrasonic waves can be categorized into guided waves and bulk waves, with the latter being commonly used in UT inspections of pipelines. Bulk waves can only detect a limited area beneath the sensor, requiring the sensor to move along the inspection surface for a full-range inspection. For ultrasonic inspection to be effective, the wavelength must be smaller than the thickness of the object being inspected; otherwise, defects may not be detected. Bulk waves propagate at constant phase and group velocities in isotropic media, and the pulses are non-dispersive.

Common ultrasonic testing (UT) techniques employed for ILI include conventional UT, Automated Ultrasonic Testing (AUT), Phased Array Ultrasonic Testing (PAUT), Internal

Rotary Inspection Systems (IRIS), and Dry-Coupled Ultrasonic Testing (DCUT). However, it is the former three that are more frequently utilized in subsea pipeline inspection, while the latter two have not yet seen widespread adoption in this context. This may be due to the need for more time for technological dissemination or constraints related to the operating conditions. The IRIS and DCUT will be discussed in greater detail in subsequent sections.

- Conventional UT/Automated Ultrasonic Testing (AUT)

A typical ultrasonic crack detection system consists of multiple sensors operating in pulse-echo mode. To ensure that the incident ultrasonic signals refract in a way that allows them to propagate at a 45° angle within the pipe, ultrasonic probes are angled appropriately [47]. Currently, the angled bulk wave pulse-echo crack detection configuration is gradually transitioning towards normal incidence. These probes generate high-frequency ultrasonic energy, introduced and propagated through the material as shear waves. In the presence of defects, some of the energy will be reflected by the defect surfaces. For wall thickness measurement, high-frequency radial signals are emitted by ultrasonic transducers perpendicular to the pipe wall, generating echoes from both the inner and outer surfaces of the pipe wall. Ultrasonic inspection uses these echo signals and records the time difference between their receptions. By comparing these with the echo signals from a healthy pipe (calibration value), differences in the echo signals are detected to identify anomalies. The first echo from the pipe's inner surface is typically defined as the first wave, while the remaining wave that penetrates the pipe wall is known as the second wave, which reflects back to the ultrasonic transducer after reaching the pipe's outer surface. The first wave can determine whether metal loss is on the pipe's inner or outer surface. When a greater distance is detected compared to a healthy pipe, metal loss on the inner surface can be inferred. If there is no change in the distance measured by the first wave, but the thickness determined by the second wave is reduced, then metal loss on the outer surface can be established.

UT is capable of the effective quantitative detection of both inner and outer corrosion defects in pipes with large wall thicknesses, including dents, bulges, metal loss, fine cracks, and coating disbondment [72]. In addition to detecting general metal loss anomalies, ultrasonic testing technology is also the only method reliable for measuring mid-wall lamination [73]. However, since the ultrasonic transducer requires liquid coupling for signal transmission, ultrasonic inspection tools can only operate in liquid environments and are more sensitive to operational conditions compared to Magnetic Flux Leakage (MFL) inspections.

The ultrasonic testing (UT) equipment developed by LIN SCAN, a company based in Abu Dhabi, United Arab Emirates, is depicted in Figure 10. LIN SCAN's UT inspection tools are meticulously designed to provide thorough and precise evaluations of pipeline integrity. With arrays of UT transducers that cover the entire 360° circumference of the pipe's interior, these tools are capable of delivering exact measurements of wall thickness and intricate analyses of wall abnormalities. The high-resolution instruments are compact, enabling straightforward deployment across a range of pipeline settings, including both launching and receiving traps. They are also adept at operating in conditions of low flow and low pressure.

Figure 10. UT ILI tool.

The UTCD tool from LIN SCAN is expressly calibrated for crack detection, identifying both longitudinal and circumferential cracks in pipelines with diameters between 16 to 36 inches. It boasts a high probability of detection (POD > 90%) and complies with industry benchmarks as per POF 2016 and the contemporary ATEX codes. Furthermore, the tool's design is optimized for use in corrosive environments and can navigate pipeline bends of up to 1.5D.

As illustrated in Figure 11, the Switzerland company PIPECARE, based in Baar, has engineered ultrasonic testing equipment that can inspect pipelines with diameters ranging from 2 to 56 inches and a wall thickness scope of 4 to 32 mm. This equipment is proficient in the detection of various defect characteristics, including metal loss, pitting, axial grooves, and circumferential grooves. It demonstrates exceptional precision in the sizing of defects, with accuracies for depth, width, and length at 0.4 mm, 5 mm, and 4 mm, respectively.

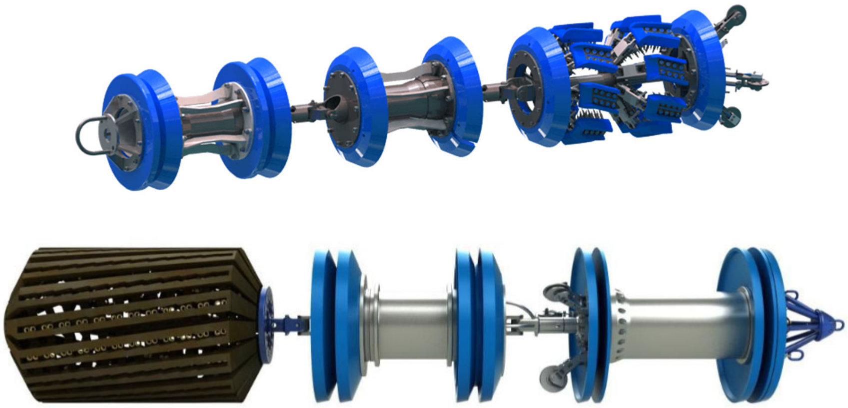

Figure 11. UT ILI tool from PIPECARE (**up**) and Baker Hughes (**down**).

The technology behind UT/AUT is now considerably mature, with the likelihood of groundbreaking advancements emerging in the foreseeable future being relatively slim. Moreover, the market's role in driving this technology forward is becoming increasingly evident, as more equipment development is undertaken by companies associated with pipeline operations. This includes expanding the range of usage, enhancing precision, broadening the pressure-bearing capacity, increasing the operational speed, and optimizing structural design. Contributions from research institutions have seen a decline compared to the early days of the technology's inception. Researchers are now focusing more on areas such as improving the matching of testing results, enhancing the accuracy of multi-source data fusion, and optimizing algorithms.

Markus R. Dann and colleagues have introduced a new automated method for matching corrosion features in ILI data, simplifying the previously manual and error-prone process. By translating the 3D matching issue into 2D, their approach leverages probabilistic models to enhance the accuracy and efficiency of feature identification. This system also quantifies and integrates match uncertainty into evaluations of corrosion progression [74]. Rafael Amaya-Gómez and his team proposed a novel method for improving the correlation of corrosion defects in MFL and UT pipeline inspections. By using Voronoi cells and iterative optimization, their technique effectively refines defect alignment while handling uncertainties. Applied to a 45 km pipeline and synthetic data, the method improves the accuracy in understanding detection probabilities and false positives [75]. Hui Wang et al. developed a Bayesian-based methodology to calibrate ultrasonic inline inspection (ILI) data and accurately estimate the actual depth of external corrosion on buried pipelines. Utilizing a clustering technique, they analyzed the soil property data to enhance the Bayesian inferential process, allowing for a more precise and probabilistic evaluation of pipeline integrity [38].

- Phased Array Ultrasonic Testing (PAUT)

In ultrasonic testing, ensuring the complete coverage of the object under examination is crucial. However, when the object has a complex geometric structure, traditional ultrasonic probes are hindered by their geometric dimensions and cannot reach certain corner areas. This leads to gaps in ultrasonic beam coverage, which can adversely affect the testing outcomes. Inspired by phased array radar technology in the last century, the concept of ultrasonic phased array testing was proposed. PAUT is an advancement over traditional ultrasonic methods, allowing for the manipulation of the ultrasonic beam through manually set parameters that control beam steering and focusing. This enables the beam to reach areas that are typically inaccessible to conventional testing methods. The advantage of PAUT lies in its ability to overcome the spatial limitations of traditional ultrasonic testing, facilitating the more comprehensive inspection of objects with complex geometries.

Tom Brown and others developed the earliest ultrasonic phased array testing system in the late 1950s. However, due to the technological constraints of that era, data processing capabilities were limited. It was not until the end of the 20th century, with the rapid advancement of low-power electronic components and other technologies, that significant progress in Phased Array Ultrasonic Testing (PAUT) was achieved. Successive introductions of related products by companies such as General Electric in the United States and the French Atomic Energy Commission marked a pivotal step forward. In China, institutions such as Tsinghua University, Harbin Institute of Technology, and Shanghai Jiao Tong University focused on technological development and equipment manufacture, significantly narrowing the gap with Western countries [76].

In the description of PAUT, it is mentioned that each array is positioned to monitor distinct segments around the circumference, ensuring minimal overlap with adjacent arrays. The ultrasound system employs a designated virtual sensor, which directs the acoustic signal as needed. To detect cracks, an angled acoustic beam is utilized: the sound wave is launched through the liquid medium and penetrates the wall of the pipe, traveling further within. In the event of a crack in the pipe wall, some of the acoustic energy would be reflected back, and this reflected signal is then detected by the same virtual sensor that emitted the original signal [77]. The precise location of the crack is determined by calculating the time it takes for the echo signals to return to the sensor. Each element of the sensor is meticulously managed by the ultrasound system, allowing any combination of elements to form a virtual sensor. In practical scenarios, adjacent virtual sensors are programmed with a slight overlap to ensure comprehensive coverage [61].

Key advantages of PAUT include comprehensive coverage with the ability to quickly scan large surface areas through beam steering and focusing, an enhanced speed due to rapid inspection capabilities, and improved accuracy from multi-angle beam emission that creates detailed asset cross-sections. PAUT offers remarkable repeatability and flexibility, especially in complex geometries and limited access scenarios. Additionally, semi-automated or motorized scanners reduce the exposure of inspection personnel to hazardous environments, making PAUT a safer alternative to radiographic testing.

Despite its many benefits, PAUT can be more costly upfront compared to conventional ultrasonics, requiring investment in sophisticated equipment and trained technicians. However, this cost is often mitigated by the efficiency and flexibility PAUT brings to inspection processes. Additional operator training is necessary to ensure the efficacy and precision of the inspection results.

PAUT has found applications across various industries, particularly in the inspection of welds on pressure vessels, piping, and tubing. It is also instrumental in detecting different types of cracking, such as Hydrogen-Induced Cracking (HIC), Stress-Oriented Hydrogen-Induced Cracking (SOHIC), and Stress Corrosion Cracking (SCC). Its use extends to the inspection of composite materials, corrosion mapping, and flaw sizing for calculations of the remaining life in assets.

PAUT has been thoroughly verified for its inspection capabilities, yet its application and research have predominantly focused on the external inspection of pipeline welds [78–80], with relatively few examples of its use in Inline Inspection (ILI). But the application of PAUT technology in ILI has a well-established history. Taking industry leaders as examples, NDT Global from Dublin, Ireland, Baker Hughes from Houston, TX, USA, and Trapil from Paris, France, their products have been extensively adopted across the domain. For instance, as shown in Figure 12, Baker Hughes' UltraScan™ Duo is a product that leverages PAUT technology initially developed by GE Healthcare in Chicago, IL, USA, for high-resolution imaging in brain, spinal, and soft tissue diagnostics. This cutting-edge technology is repurposed to enhance pipeline integrity by providing superior data resolution and precision during ILI procedures. The UltraScan Duo employs a combination of adaptable perpendicular and angled ultrasonic beams, which significantly improves both the Probability of Detection and the Probability of Identification for various types of cracks and metal loss defects. It boasts the capability to detect cracks as small as 25 mm in length with a minimum depth of 1 mm.

Figure 12. Baker Hughes' UltraScan™ Duo.

As illustrated in Figure 13, NDT Global's PROTON™ represents a significant evolution in ultrasonic phased array inspection technology, particularly adept at tackling the complexities of seam-weld geometries in pipelines. It stands as a robust alternative to hydrostatic testing, with the ability to detect and characterize pipeline cracks accurately, avoiding damage to assets and interruptions in service. PROTON™ refines the inspection workflow, allowing for a flexible configuration via firmware to adapt to various inspection scenarios, such as crack detection and metal loss assessment. This innovation has empowered operators to move away from hydrostatic testing, thereby boosting safety and operational efficiency.

Figure 13. PAUT ILI tool from NDT Global and Trapil.

2.4. Eddy Current Testing (ECT)

- Conventional ECT

ECT is an NDT method that utilizes the principles of electromagnetic induction to detect flaws in materials. When ECT is used in the pipeline, once the excitation coil is energized with an alternating current, an alternating primary magnetic field is formed around the coil. This primary magnetic field induces eddy currents on the pipe wall, which in turn generate a secondary magnetic field in the opposite direction to the main magnetic field. When there is a defect in the pipe wall, it causes variations in the induced eddy currents and subsequently affects the secondary magnetic field. The detection coil measures changes in the magnitude and phase of the induced voltage to obtain information about the defect parameters.

One of the primary limitations of eddy current testing is its depth of penetration, fundamentally due to the skin effect. The penetration depth of the induced eddy currents is inversely proportional to the square root of the test frequency, which typically ranges from a few hertz to several megahertz (and, in special cases, can be as high as several hundred megahertz). Consequently, the skin depth is generally shallow, positioning eddy current testing as a non-destructive inspection technique predominantly for assessing surface or near-surface integrity. Eddy current testing is efficient in detecting defects like metal loss, cracks, and corrosion, but it is less effective for non-magnetic pipelines.

As shown in Figure 14, the gradation in eddy current density is most pronounced at the material's surface proximal to the coil and progressively attenuates with increasing depth. This skin depth effect is characterized by a standard depth of penetration, at which point the eddy current density falls to 37% of its surface value. Influential factors that affect this standard penetration depth include the test frequency, the material's electrical conductivity, and its magnetic permeability.

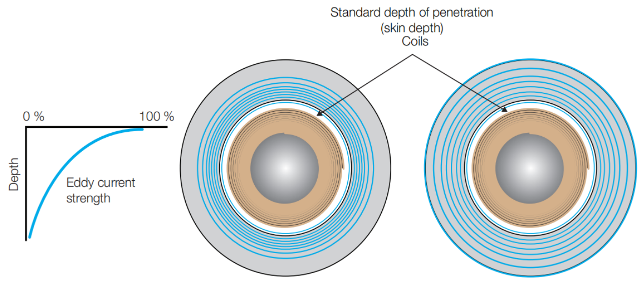

Figure 14. Schematic of the skin depth effect.

Currently, ECT is primarily applied to the detection of land-based buried pipelines. The ECT technology is not yet fully mature for offshore pipeline inspections, where its application remains relatively limited. Few companies have ventured into the market for ECT technology in offshore pipeline inspection. A notable example is i2i Pipelines Ltd. from Manchester, UK, whose ECT inspection tool is illustrated in Figure 15. Therefore, there is a need for further research and innovation in ECT technology to overcome the challenges posed by the marine environment and to advance its application in the field of offshore pipeline inspection. These challenges include but are not limited to issues related to sealing, underwater equipment deployment, and the inherent difficulties associated with remote operations compared to land-based operations.

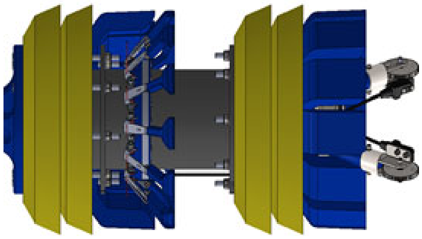

Figure 15. The ECT inspection tool from i2i Pipelines Ltd., Manchester, UK.

- Pulsed Eddy Current Testing (PECT)

Unlike traditional eddy current testing systems, PECT inspection typically utilizes pulse-shaped square wave signals as the excitation signals. When this pulse-shaped square wave is applied to the excitation coil of the probe, a periodic pulsed current, corresponding to the cycle of the pulse signal, is generated. This results in a rapidly decaying pulsed magnetic field, known as the source field, around the excitation coil [81]. As the probe approaches the test object, this pulsed magnetic field induces transient eddy currents in the conductive test specimen. These pulsed eddy currents, as they propagate into the interior of the test specimen, induce a rapidly decaying magnetic field within the conductor. The detection coil or sensor can sense this eddy current magnetic field, detecting transient induced voltage signals that vary over time. The response, when represented on a logarithmic scale, indicates that over time, the signal originates from progressively deeper layers within the metal. There is a distinct alteration in the decay rate of the response that signifies the thickness limit of the metal sheath; a thicker wall results in a postponed transition in this decay rate.

When defects or cracks are present on the test specimen, they alter both the intensity and the distribution of the eddy current magnetic field, causing changes in the transient induced voltage sensed by the detection coil or magnetic sensor. Thus, variations in transient-induced voltage provide information about the size and structural parameters of defects on the test object.

A key advantage of this technique, distinguishing it from others, is its capability to provide absolute readings of wall thickness. This makes it particularly suitable for monitoring applications, where a stationary sensor continuously measures wall thickness over extended periods. A limitation, however, arises from the use of a broader frequency band, which prolongs the duration of a single measurement, making PECT less practical for use in scanning tools. Accurate measurements require the sensor to be stationary.

The advancement of Pulsed Eddy Current Testing (PECT) and its deployment in the oil and gas sector were pioneered by Shell Global Solutions [49]. PECT is notable for its various applications, a primary one being the absolute measurement of wall thickness in pipes, especially in offshore settings. However, the practical application of PECT for the high-speed In-Line Inspection (ILI) of pipelines is challenging due to the extended detection time required for the sensor response and the reduced sensitivity resulting from significant motion. Consequently, efforts have been directed towards accelerating the PECT inspection speed. Moreover, the development of new sensor technologies that offer deeper signal penetration, enhanced detection sensitivity and linearity, as well as the capability to discern between internal and external defects (ID/OD discrimination) is currently a focal point of research [81,82].

- Remote Field Eddy Current Testing (RFEC)

RFEC technology, originally termed as Remote Field Eddy Current, was discovered by W.R. MacLean in 1951 and subsequently patented under the title "An Apparatus for Measuring the Thickness of Iron Pipe Using Magnetic Techniques". Its first commercial application was in 1959 for the inspection of oil well casings. Shell also developed the first RFEC pipeline inspection device, which was introduced in 1961. In China, RFEC technology has been widely applied since the 1990s for the intelligent internal inspection of buried oil and natural gas pipelines.

RFEC detectors can be used in conditions where traditional ultrasonic and magnetic flux leakage methods are ineffective. The advantage of RFEC equipment is its ability to induce both an axial magnetic field and a circumferential electric field (eddy currents). Because it can generate both types of energy fields, RFEC technology is unique in its ability to detect defects in both axial and circumferential directions without the need for supplementary techniques.

As shown in Figure 16, the working principle of RFEC technology involves detecting changes in the alternating electromagnetic field emitted by the sensor. This field interacts with the metal pipeline and is enhanced at locations where there is metal loss. The electromagnetic field is captured by receiving sensors, converted by an analog-to-digital converter, and processed by a digital processor. The inspection data are stored within the detector.

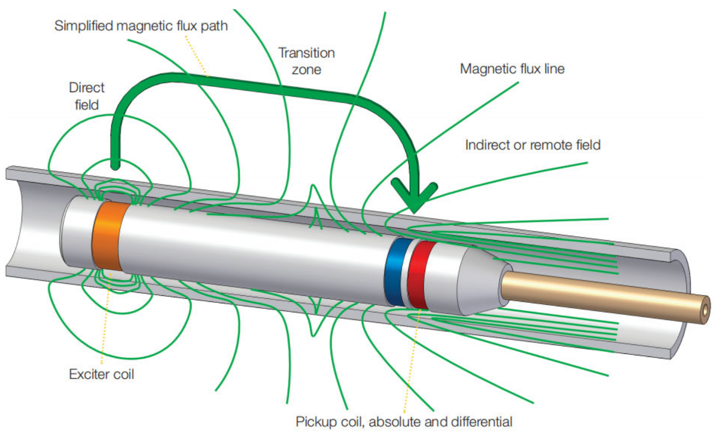

Figure 16. Work principle of RFEC.

RFEC technology is applicable to, for example:

1. Pipelines with internal rust, scaling, or significant wax buildup.
2. Pipelines containing bends with small radii, tees, and reducers.
3. Lined pipes (cement, high-density polyethylene, clay).
4. Cast iron pipelines with nodularity.

2.5. Electromagnetic Acoustic Transducer (EMAT)

EMAT technology, broadly speaking, falls under the umbrella of ultrasonic testing methods. As shown in Figure 17 (left), the distinguishing feature of EMAT, compared to conventional ultrasonic testing, lies in its method of generating ultrasonic waves through electromagnetic means rather than piezoelectric generation. EMAT is the core of electromagnetic ultrasonic technology, encompassing both the excitation and reception components, and forms an integral part of the electromagnetic ultrasonic testing system along with the object under examination. The working mechanism of EMAT is quite complex, involving interplay and energy conversion among electromagnetic fields, solid mechanics fields, and acoustic fields. Figure 17 (right) displays the EMAT inspection equipment used by PIPECARE, a company based in Baar, Switzerland.

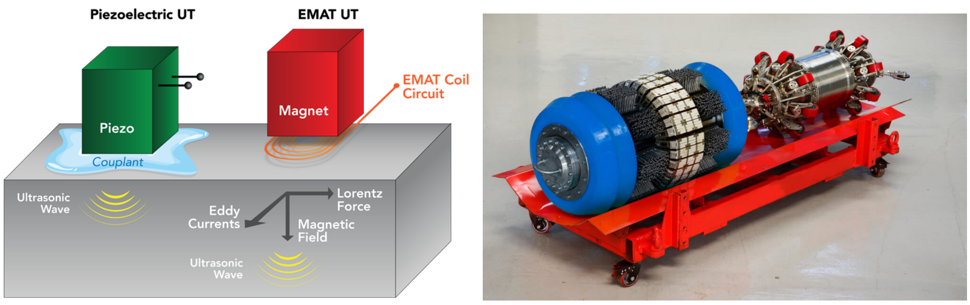

Figure 17. The Difference Between the Piezoelectric UT and EMAT UT (**Left**) and EMAT ILI tool (**Right**).

EMATs can typically be classified into three types: bulk wave EMATs, guided wave EMATs and EMATS generate both body and guided waves. For non-ferromagnetic materials, bulk-wave electromagnetic acoustic transducers typically utilize Lorentz forces to propagate waves. In the case of ferromagnetic materials, ultrasonic waves are generated based on magnetostrictive forces. Correspondingly, the ultrasonic guided waves produced by electromagnetic acoustic guided wave transducers are confined within the confines of the pipeline. The commonly used types of guided waves are Lamb waves and SH waves (horizontally polarized shear waves).

The complexity, diverse influencing factors, and broad application prospects of EMATs have attracted extensive research attention. In 1999, Masahiko Hirao and others designed an electromagnetic acoustic guided wave transducer capable of generating SH waves, based on periodic permanent magnets [83]. In 2004, Koorosh Mirkhani and colleagues developed a finite element model for EMATs. This model, considering the spatial inhomogeneity of magnetic flux density, accurately assessed the ultrasonic pulse emissions from EMAT transmitters [84]. In 2014, Shu Dahai investigated the generation mechanism of electromagnetic acoustic longitudinal guided waves. He derived their mathematical representation and conducted a structural design for EMATs. Through finite element simulation, he analyzed the propagation characteristics of longitudinal guided waves in pipelines and the impact of various defects on these waves [85]. In 2019, Xing Yanhao innovatively carried out research on helical guided-wave technology for pipeline crack detection. He proposed an analytical method for ultrasonic guided waves using a multimodal analysis of helical waves and established a theory for controlling the propagation direction of electromagnetic acoustic helical guided waves in three-dimensional pipelines [86]. In 2023, Xu Zhang and others developed a unidirectional EMAT based on circumferential Lamb waves (CLamb waves). Through the optimization of structural parameters and the adjustment of excitation frequency, they successfully generated high-amplitude, low-dispersion CLamb waves in the high-frequency thickness product region of dispersion curves [87].

As shown in Figure 18, taking Baker Hughes' EmatScan CD as an example, the EmatScan CD is ideally engineered to detect a comprehensive array of crack-like anomalies. From the deformation cloud diagram it generates, it can be observed that it includes the detection of Stress Corrosion Cracking (SCC) colonies. Additionally, other defects such as sub-critical SCC, longitudinal fatigue cracks, toe and hook cracks, lack-of-fusion cracks, as well as cracks situated in or near the long seam weld, can also be detected. The detailed technical specifications are presented in Table 1.

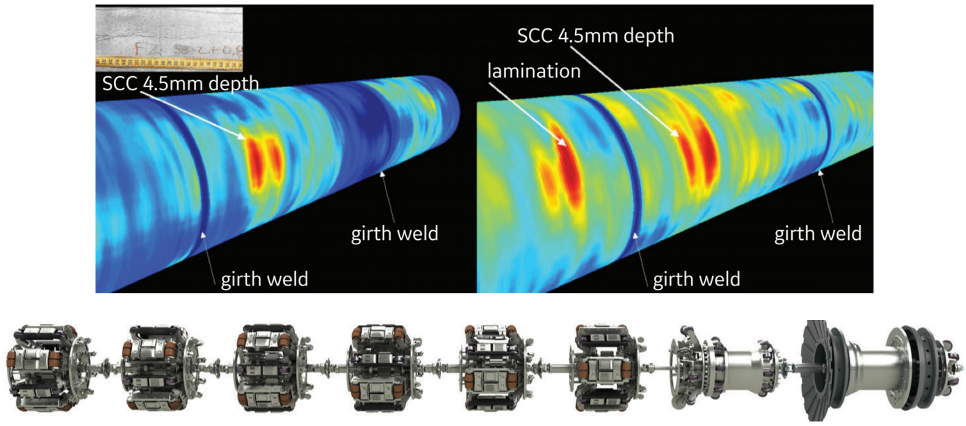

Figure 18. Baker Hughes' EmatScan CD and deformation cloud diagram it generates.

Table 1. Technical specifications of Baker Hughes' EmatScan CD.

Property	Gen 3
Size range	24 to 36 inch.
Inspection range	Up to 220 kilometers (136 miles)
Speed range (at full resolution)	Up to 2.5 m/s (5.5 mph)
Bend passing	1.5D (back-to-back on request)
Minimum defect size *	2 × 50 mm
POI %achieved to date *	>80%
POD %achieved to date *	>90%
Detection redundancy *	Multiple

* base material and seam weld for all coating types.

Research in the relatively nascent field of EMATs for ILI technology is ongoing. Y. Yan et al. introduced a novel deep learning approach for the automatic identification of pipeline girth weld cracks, employing a sophisticated Convolutional Neural Network (CNN) combined with a pre-trained Support Vector Machine (SVM) classifier [88]. Pouyan Khalili and Peter Cawley recommend using diverse inspection methods for corrosion detection at hard-to-reach spots such as pipe supports. The A1 mode, with its short wavelength, is suggested for pinpointing sharp, localized pitting, while long-range guided waves are suitable for detecting wider thinning. The SH1 mode is particularly good for gradual defect identification and works in various morphologies [89].

2.6. Acoustic Resonance Technology (ART)

Acoustic Resonance Technology (ART) emerges as a novel solution to the challenges traditionally faced by ultrasonic inspection tools, which typically depend on a liquid medium for pipeline assessments. This constraint has been particularly problematic in the inspection of gas pipelines. As shown in Figure 19, ART circumvents the requirement for a liquid interface by employing a transducer that emits a broad-spectrum acoustic signal directed at the pipeline wall. This signal is of a duration long enough to initiate sustained oscillations within the structure of the wall [90].

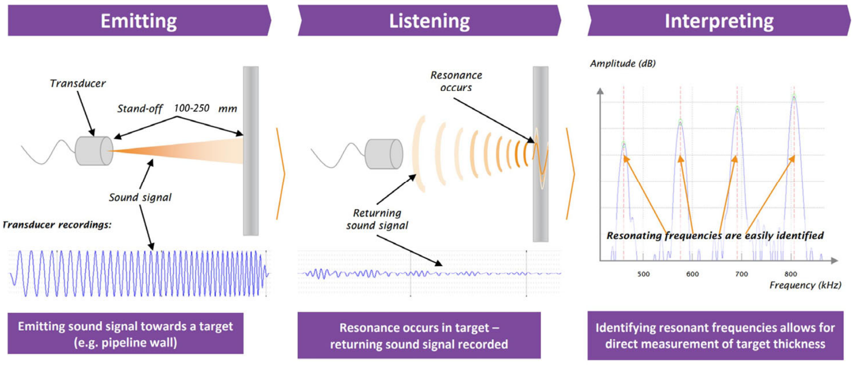

Figure 19. Work principle of ART.

As the wall vibrates, the continuous impact of the acoustic waves causes these oscillations to resonate, significantly amplifying them. This resonance effect produces standing waves that manifest as a unique frequency pattern, which is directly influenced by the wall's material properties and thickness. The ART device captures the acoustic echoes resulting from these standing waves, and the analysis of the reflected sound reveals a distinctive resonance signature.

It is this resonance signature that provides precise information about the pipeline wall's characteristics. By analyzing the frequencies at which the wall naturally resonates, ART can deduce the wall's thickness without the need for a liquid medium. Consequently, ART enables the effective ultrasonic inspection of gas pipelines, overcoming the limitations of traditional inspection methods and enhancing the safety and maintenance of pipeline infrastructure.

ART was first unveiled in 2013 and has rapidly established itself as a highly versatile tool in the field of diagnostics. Presently, companies like NDT Global and TSC Subsea are pioneering the application of ART in pipeline inspection. As shown in Figure 20, TSC Subsea, based in Milton Keynes, UK, is at the forefront of external pipeline inspection, while NDT Global is a leading example in the domain of internal pipeline inspection.

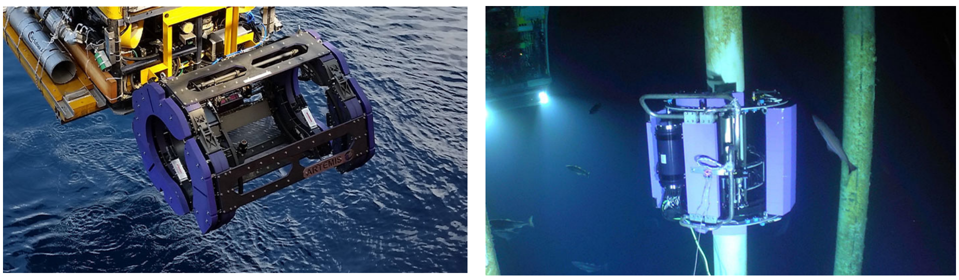

Figure 20. TSC Subsea's ART ILI tool.

NDT Global's ART ILI tool, as depicted in Figure 21, employs an ultra-wideband signal ranging from 400 kHz to 1.1 MHz. This versatile frequency range enables the inspection tool to operate effectively in both gaseous and liquid environments. Moreover, it facilitates the corrosion inspection of pipelines with wall thicknesses up to 100 mm, maintaining the same depth sizing accuracy of ± 0.4 mm that is characteristic of high-resolution ultrasonics.

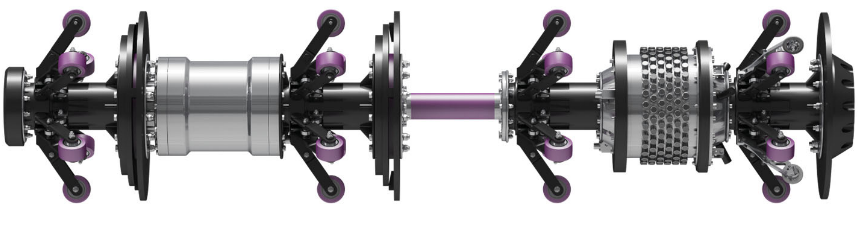

Figure 21. NDT Global's ART ILI tool.

The ART tool's sensor array conducts two primary measurements. The first is the conventional time of flight (TOF) measurement, which is used to detect anomalies such as dents and buckles, as well as to assess the pipeline's straightness and ovality. The second measurement is derived from a tail signal, indicative of the wall thickness of the subject pipeline. Through frequency analysis of the reflected signal, the tool is able to directly measure structural thickness. Wall thickness measurements are extracted from the resonance frequency bands. This innovative approach ensures that accuracy does not deteriorate with increasing wall thickness or with higher tool velocities—a significant advantage over traditional methods.

Additionally, the non-contact nature of the sensors allows for a comprehensive ultrasonic geometry survey without the need for supplementary modules. This includes standard assessments of pipeline integrity such as dents, buckles, out-of-straightness, and ovality, all captured through the TOF data component. The integration of these features into the ART inspection protocol underscores the tool's sophistication and reinforces its capability for delivering detailed, reliable assessments of pipeline health.

3. Pipeline Inspection Gauge (PIG)

Pipeline systems often face issues such as the accumulation of water, paraffin, wax, and hydrates, which can lead to imperfections in the pipes and affect the efficiency of transportation. To prevent these problems, integrity management plans are essential for the proper maintenance of pipelines and related assets. These plans are incorporated into a simplified system known as the Pipeline Integrity Management System (PIMS), which is used for this purpose [91].

Initially, pigging was a method considered within PIMS to prevent internal corrosion and other issues in pipelines as part of maintenance plans. Moreover, tasks like dewaxing, descaling, and hydrate removal are all part of the cleaning duties performed by PIGs within pipelines.

However, with increasing demands and technological advancements, the role of PIGs has evolved. As shown in Figures 22 and 23, today's PIGs integrate a variety of Non-Destructive Testing (NDT) tools. Pipeline inspection technologies based on Magnetic Flux Leakage (MFL), Ultrasonic Testing (UT), Eddy Current Testing (ECT), and Electromagnetic Acoustic Transducers (EMAT) each have inherent limitations. The use of a single technique often fails to detect pipeline defects efficiently, accurately, and comprehensively. As a result, PIGs that integrate multiple inspection technologies have become a more effective solution. These PIGs are propelled through the pipeline by the differential pressure of the fluid within, moving along with the flow and carrying inspection equipment that outputs data in real-time through wireless transmission modules [92].

Figure 22. TDW's PIG (DEF + SMFL + MFL + LFM + EMAT).

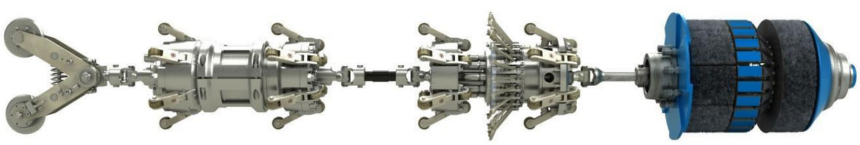

Figure 23. PII's MagneScan™.

The practical application of PIG technology in pipeline inspection was first realized by Tuboscope, a company in the United States. PIGs typically use Deformation Detection (DEF) to capture changes in the pipeline's internal geometric dimensions. They employ odometers, Inertial Measurement Units (IMUs), visual sensors, and the Global Navigation Satellite System (GNSS) to track the pipeline's trajectory (XYZ coordinates) [93]. For the precise localization of the PIG within the pipeline, a variety of Kalman Filter-based techniques are used, including the Extended Kalman Filter (EKF) and the Unscented Kalman Filter (UKF). Anjum and colleagues have further refined the UKF method to account for special circumstances such as slippage, optimizing correction, and precision [94].

NDT methods are employed to investigate various defect points within pipelines, examining internal surfaces, external surfaces, and wall thicknesses to identify characteristics like cracks, metal loss, wall thickness variations, and corrosion [48]. Common defect types include metal loss defects, seam weld defects, stress corrosion cracking (SCC), hook cracks or seam weld cracks, hydrogen-induced cracks, fatigue cracks, shrinkage cracks, a lack of fusion, circumferential cracks, and cracks in dents. These findings contribute to a range of Integrity Assessments, such as Fitness-for-Purpose (FFP), Crack Threat Integrity Assessment, and Crack Growth Assessment.

However, the serial connection of multiple inspection devices has traditionally resulted in poor passability through large deformation sections, necessitating a relatively larger turning radius. Furthermore, in the event of a blockage, the repair costs for pipeline robots can be substantial. If the pipeline in question is a subsea pipeline, these costs can become even more exorbitant. Decades of meticulous research and structural innovation have culminated in a marked decline in the bend radius required for the operation of pipeline inspection robots, facilitating their navigation through tight corners. This advancement has effectively halved the standard bend radius from the conventional triple the pipeline diameter (3D) to an optimally reduced one and a half times the diameter (1.5D). In addition, the development of multi-diameter-compatible Pipeline Inspection Gauges (PIGs) has considerably mitigated the risk of blockages. These enhancements have not only improved the robots' passability through sections prone to large deformations but have also expanded their applicability across various pipeline sizes, ensuring a more streamlined inspection process.

The oil and gas industry's expansive scale has necessitated a comprehensive infrastructure of subsea pipelines, catalyzing growth in associated sectors such as pipeline laying, pigging, internal inspection, external inspection, monitoring, maintenance, and health assessment. Among these, the critical domain of pipeline internal inspection has garnered substantial technological and financial investments globally.

Since the inception of subsea pipeline installation, the swift escalation in total pipeline mileage, compounded by aging infrastructure, has led to a significant portion of these pipelines requiring large-scale re-inspection and maintenance. Companies from Europe, the United States, and Japan were the pioneers in this field and have, over time, developed a wide array of maintenance technologies and established comprehensive standards. However, emerging players, particularly from Saudi Arabia and China, have been rapidly advancing, closing the technological and equipment gap, though there is still a considerable disparity in their current levels of expertise. Figure 24 illustrates the major global commercial entities and their respective countries involved in this sector.

For decades, the evolution of subsea pipeline inspection has been propelled by a synergy between commercial enterprises and academic institutions, with continuous innovation and the incorporation of various NDT techniques enhancing the precision, multidimensionality, and accuracy of pipeline inspections. Presently, there is a noticeable shift towards commercial entities driving progress, with scientific research increasingly focusing on the integration of multisource data fusion, implementing neural networks and big data methodologies to enrich pipeline health assessments, and enabling quicker, more precise, and comprehensive evaluations. ILI provides extensive data, which serve as a solid foundation for Health and Structural Integrity. Vladimír Chmelko et al. have conducted comprehensive research on the defect safety assessment and structural health evaluation of pressurized pipelines [95,96].

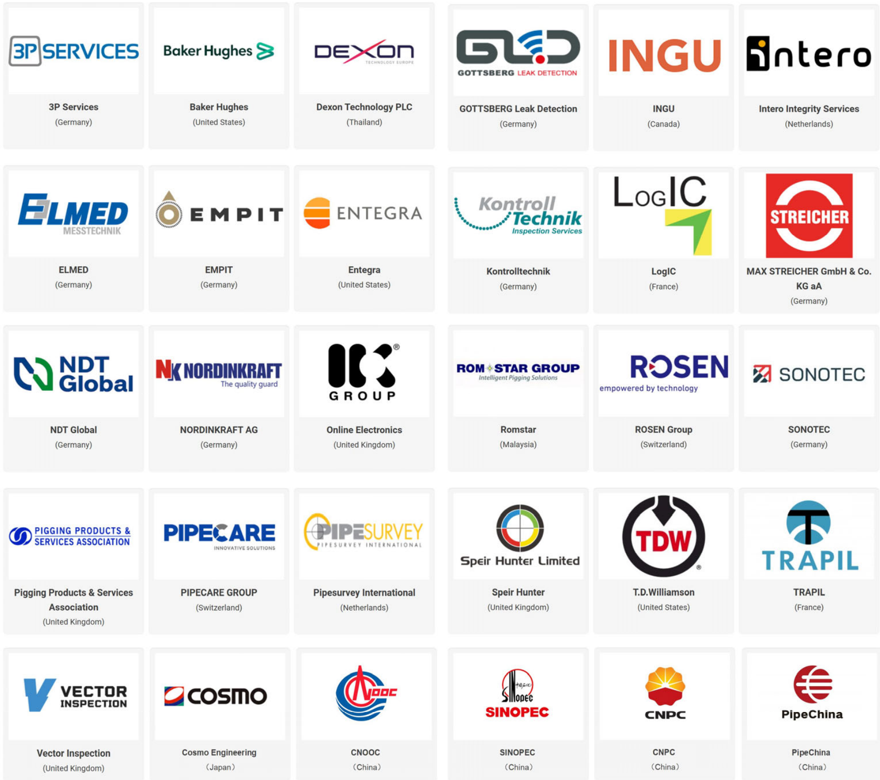

Figure 24. The major global companies of ILI.

4. Possible New Technologies

The applicability and innovation of technologies in the field of subsea pipeline inspection are vital. Although certain technologies may not initially be suitable for the complexity and harsh conditions of the subsea environment, future research and enhancements could render them viable. Here is an extended discussion on two original technologies that, with redesign and optimization, could potentially be adapted for subsea pipeline inspection tasks.

4.1. Internal Rotating Inspection System (IRIS)

IRIS is a distinct variation of UT, functioning on the principle illustrated in Figure 25. IRIS relies on a transducer that generates ultrasonic pulses parallel to the axis of the pipe being tested. The ultrasonic waves are then directed perpendicularly into the pipe wall by a reflector. The rotation of the reflector is driven by a small turbine, which is powered by the medium within the pipe. Similar to conventional ultrasonic testing, a portion of the ultrasonic waves is reflected by the inner wall, while the remainder is reflected by the outer wall. As the velocity of ultrasonic waves in the pipe material is known, the thickness of the wall can be assessed by calculating the difference in flight time between the echoes.

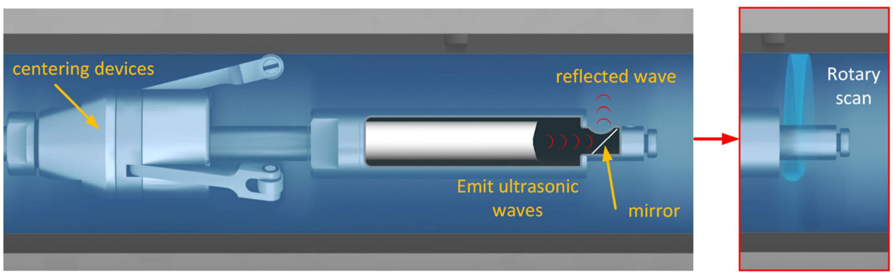

Figure 25. The principle of IRIS ILI.

As shown in Figure 26, a key to the quality of IRIS inspection is ensuring that the reflector is centered within the pipe, as eccentricity or wobble can produce distorted scan images. The Olympus, located in Tokyo, Japan, its ILI tool, embracing IRIS technology, epitomizes an advanced ultrasonic inspection method, markedly efficacious for exhaustive scrutiny within the petrochemical industry and for evaluations of balance-of-plant tubing. This refined modality is adept at gauging wall thickness variations, discerning material degradation, and ascertaining flaw orientations in tubes with internal diameters from 0.5 to 3 inches. It is meticulously engineered to conduct thorough inspections of tube and shell heat exchangers, air-cooled heat exchangers, and boiler tubes, delivering superior accuracy in the detection and characterization of potential defects, thereby bolstering the safety and reliability of these critical components.

Figure 26. Olympus' IRIS ILI tool.

IRIS can detect corrosion, pitting, and wall loss and is most commonly used for tube inspection in boilers, heat exchangers, air coolers, and feed water heaters. It is particularly versatile as it is suitable for both ferrous and non-ferrous materials, and IRIS can be used on a wide range of tube diameters and wall thicknesses. Companies producing inspection equipment based on IRIS technology include Eddyfi Technologies in Quebec City, QC, Canada; APPLUS in Barcelona, Spain; and Olympus in Tokyo, Japan, among others. However, while IRIS is commonly used for inspecting heat-exchanger tubing, there are no instances of its use for subsea pipeline inspection to date.

4.2. Dry-Coupled Ultrasonic Testing (DCUT)

DCUT offers a cost-effective and environmentally friendly solution for the inspection of a wide array of materials, both metallic and non-metallic, negating the requirement for liquid couplants. Capable of accommodating high voltages, DCUT utilizes diverse transducer types such as flexible, contact, wheel, and remote UT transducers, as illustrated in Figure 27. This breakthrough in non-destructive evaluation harnesses cutting-edge high-voltage piezoelectric transducers that proficiently propagate ultrasound through a rubber medium, bypassing the necessity for conventional liquid couplants. This pioneering method mitigates issues related to liquid couplants, such as the risk of environmental harm, potential damage to components, and ancillary expenses. Additionally, DCUT extends the versatility of ultrasonic examinations to a more comprehensive range of material forms and geometries.

Figure 27. Types of dry-coupled UT transducers.

The advent of flexible, thin-profile transducers through DCUT enables the swift and precise detection of flaws and the measurement of material thickness, even on intricate configurations. This is further complemented by the incorporation of wheel probes and remote contact sensors, which facilitate extensive scanning and access to otherwise unreachable areas. When combined with high-power UT instruments, DCUT transducers streamline the inspection workflow, excising the logistical and financial burdens associated with couplant usage. As a result, DCUT not only enhances the efficiency of inspection practices but also offers a more sustainable, cost-effective, and adaptable option for industrial inspection demands, thereby expanding the capabilities of ultrasonic testing without compromising on accuracy or dependability. However, despite its benefits, DCUT's application within the natural gas pipeline sector remains limited and has not yet met the foundational requirements for in situ use on underwater pipelines.

5. Conclusions

In this paper, we have delved into the array of advanced technologies in the field of subsea pipeline ILI. Through careful selection, we focused on a range of inspection technologies including DEF, MFL, UT, ECT, EMAT, and ART. The operational principles, detection characteristics, and applications of each technology in ILI devices have been exhaustively elucidated.

Particularly for the widely used MFL, UT, and ECT technologies, we provided not only insights into their principles and features but also explored their sub-technologies and corresponding inspection equipment. This paper offers in-depth understanding and practical guidance for technology selection, ensuring comprehensiveness and efficiency in detection tasks.

Additionally, we conducted meticulous analyses of smart PIG devices that integrate multiple inspection technologies. Such devices significantly enhance the accuracy and efficiency of inspections by leveraging the strengths of various techniques. The discussion also includes a forward-looking exploration of emerging technologies that may be applied to subsea pipeline inspections in the future.

Despite the comprehensive overview provided on subsea pipeline inspection technologies, it is important to emphasize that ILI alone cannot furnish a complete assessment of pipeline health. Certain types of defects and issues may require supplemental external detection methods for accurate characterization and identification. For example, integrating external detection methods such as radiographic imaging, fiber optic sensing technologies, and dry chamber visual inspections can provide critical information that internal inspections might miss. This complementary strategy of internal and external inspections can provide a more holistic and multidimensional assessment framework for pipeline integrity management.

In summary, although current subsea pipeline inspection technologies are highly advanced, the future direction should focus on the integration and innovation of these technologies. By maintaining synergy and complementarity between internal and external inspections, we can further enhance our monitoring capabilities of subsea pipeline health, ensuring the safety and reliability of energy transmission.

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Abbreviations

ILI	In-line inspection	NDT	Non-destructive Testing
PIG	Pipeline Inspection Gauge	DEF	Geometry deformation mapping
MFL	Magnetic Flux Leakage	UT	Ultrasonic Testing
ECT	Eddy Current Testing	EMAT	Electromagnetic Acoustic Testing
ART	Acoustic Resonance Technology	DAMC	Direct Arm Measurement Caliper Angle or Movement Sensor
IEMC	Indirect EM Caliper	IMU	Inertial measurement units
ULF	Ultra-low frequency	GPS	Global Positioning System
LFM	Low Field Magnetic Flux Leakage	GMFL	Gas Magnetic Flux Leakage
PECT	Pulsed Eddy Current Testing	SMFL	SpirALL® Magnetic Flux Leakage
CNOOC	China National Offshore Oil Corporation	CASIC	China Aerospace Science and Industry Corporation
NMSE	Normalized mean square error	CNN	Convolutional neural network
THMS-Net	Two-stage heterogeneous signals mutual supervision network	AUT	Automated Ultrasonic Testing
PAUT	Phased Array Ultrasonic Testing	IRIS	Internal Rotating Inspection System
DCUT	Dry-Coupled Ultrasonic Testing	HIC	Hydrogen-Induced Cracking
SOHIC	Stress-Oriented Hydrogen-Induced Cracking	SCC	Stress Corrosion Cracking
ID	Internal diameter	OD	Outside diameter
RFEC	Remote field eddy current	RVI	Remote Visual Inspection
TOF	Time of flight	GNSS	Global Navigation Satellite System
EKF	Extended Kalman Filter	UKF	Unscented Kalman Filter
FFP	Fitness-for-Purpose		

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