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Monitoring of Critical Metallic Assets in Oil and Gas Industry Using Ultrasonic Guided Waves

Anurag Dhutti, Shehan Lowe and Tat-Hean Gan

Abstract

This chapter presents advancements in structural health monitoring (SHM) using ultrasonic guided waves (UGW) technology for metallic structures to support their integrity and maintenance management. The focus is on pipelines and storage tanks, which are critical assets in the Oil and Gas industry, whose operational conditions can greatly accelerate damage mechanisms. Conventional routine inspections are both costly and time consuming and affect the plant reliability and availability. These operational and economic disadvantages have led to development of SHM systems which can be permanently installed on these critical structures to provide information about developing damage and optimise maintenance planning and ensure structural integrity. These technology advancements enable inspection without interruption to operations, and generate diagnosis and prognosis data for condition-based maintenance, hence increasing safety and operational efficiency. The fundamentals, architecture and development of such SHM systems for pipes and above ground storage tanks are described here.

Keywords: ultrasonic guided waves, structural health monitoring, permanently installed, monitoring data analysis, defect detection, optimised maintenance planning

1. Introduction

Petroleum oil refining is an essential industry and an important element of the economic infrastructure. Refineries are large compared to other industrial plants because their production and storage capacities are designed to assure volume profitability. The industry deals with considerable amounts of flammable and toxic substances and is thus inherently hazardous. If loss of containment is not prevented or controlled, it can have serious economic and environmental consequences. The reduction of accidents is driving the development of better control technologies and risk management strategies. Corrosion remains one of the challenges which is further elevated because of ageing infrastructure and variation in concentration of crude oil.

According to a report from eMARS (Major Accident Reporting System) [1], corrosion of equipment is an important source of accidents in refineries, being responsible for one in five major refinery accidents occurring in the EU since 1984. The magnitude of a refinery unit and the complexity of the processes are great and a wide variety of equipment such as trays, drums and towers are subject to corrosion problems. The pipeline infrastructure and storage tanks are particularly vulnerable

and have high risk profiles due to the volumes they may contain. The same report analysed 99 corrosion failures, 71% of them originated in pipe works and 15% of them occurred in storage tanks.

Pipelines serve as basic components of refinery infrastructure as well as the chief transmission line between refineries and remote sites delivering the products to distribution points and customers. They are generally constructed from a variant of carbon steel and so are naturally susceptible to corrosion. The intense temperatures and temperature fluctuations, and presence of corrosive agents can accelerate the corrosion process. Corrosion can cause oil leaks which may lead to explosion with severe consequences. One example is an underground oil pipeline operated by Sinopec, China's largest oil refiner [2], which exploded following an oil leak due to corrosion. The blast killed 44 people and injured 136, and led to disruption in electricity and water supply and evacuation of around 18,000 people.

Failure of storage tanks is not as prevalent as pipe work failures but due to the hazardous substances stored, they are well represented in major accidents in the process industries. Storage tanks are extensively used in refineries to store fossil fuel, acids, solvents, benzene, sour water, asphalt and related products (heated storage). Both types of storage tanks are vulnerable to corrosion. Crude oil storage tanks suffer more aggressive corrosion compared to other refinery equipment due to the oil sulphur content. Another study on storage tank accidents [3] showed that 74% of accidents involving them occurred in Petro-chemical refineries with 85% of the accidents leading to fire and explosions. One such incident happened at a fuel storage facility in Brazil in 2015 [4] which took more than 4 days to bring under control with 110 firefighters, road blockages and the shut-down of ports (**Figure 1**).

Over the years, numerous non-destructive testing (NDT) techniques have been used to inspect the condition of pipelines and storage tanks, e.g. penetrant testing, magnetic particle testing, radiography, eddy current, thermography, acoustic emission and conventional ultrasonic testing [5]. Many of these techniques only offer localised inspection. Pipe inspection using these techniques requires removal of insulation to access pipe surfaces and may even require erection of scaffolding for difficult-to-access locations. For storage tanks, exterior corrosion, whether general or localised at crevices, is easy to detect using the aforementioned inspection methods. But for inspection of internal tank floors from exposure to corrosive agents in the product, requires the tank to be emptied and cleaned to gain access. These operations are both time-consuming and expensive and cannot be used in-service.

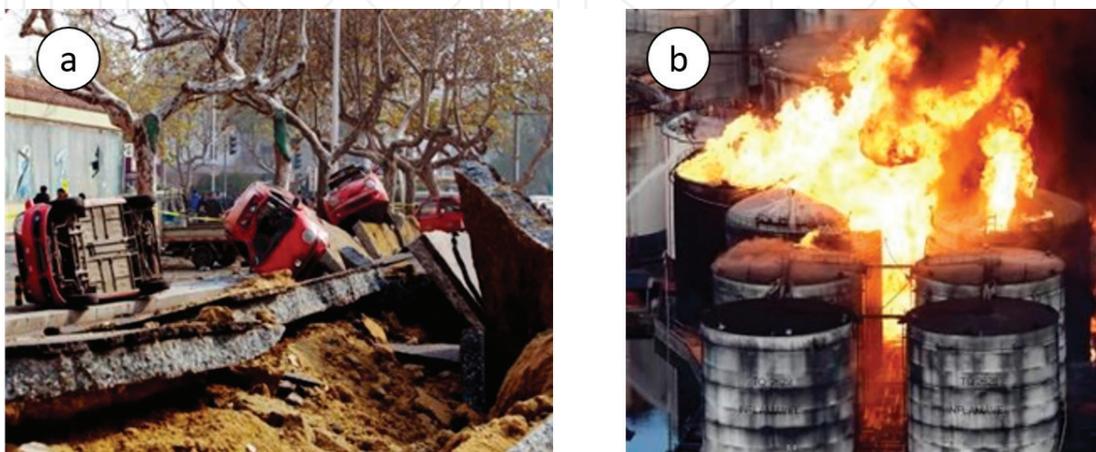


Figure 1. The damage from (a) oil leakage of a corroded buried pipeline in China [2] and (b) tank at a fuel storage facility in Brazil [4], which led to explosions with severe consequences and put human in danger.

Less than rigorous inspection is considered a major cause of corrosion failure [1]. For this reason, there has been increased emphasis on the development of damage prognosis systems that inform the operator of a structure's health and of any developing damage. This will enable accurate estimation of the remaining useful life of the structures and can transform maintenance procedures from schedule-driven to condition-based implementation. These systems will significantly decrease the time these structures are offline, hence cutting life-cycle costs and labour requirements. Structural Health Monitoring (SHM) serves an essential part of any damage prognosis system. It monitors the structures whilst they are in-service and provides information about any detected damage.

The integration of Guided Wave Testing (GWT) technology into SHM is growing rapidly as it offers a remote solution with the ability to screen large structures. This chapter will detail the advances in SHM technologies using GWT for the two most critical metallic components in the Oil & Gas industry: pipelines and storage tanks. A brief description of GWT and the underlying physics of Ultrasonic Guided Waves (UGW) for tubular and plate like structures is provided. Its application to SHM of pipelines and storage tanks is described and the state-of-the-art in the enabling technologies including transducers and their coupling (transducer system) and data processing is presented. The design, operation and performance of SHM devices for pipelines and storage tanks are presented, and their current limitations are highlighted to direct future research and development activities.

2. Background of guided wave technology

Much research has been conducted on the use of UGWs to inspect elongated engineering structures, i.e. pipes, plates, rails and cables, because of their inherent long range propagation [6]. Commercial GWT systems have evolved vastly over the past two decades to fulfil many industrial inspection requirements. For pipes, initial realisation of UGW propagation in cylindrical structures by Gazis et al. [7], Zemanek [8] and Silk and Bainton [9], led to initial development of a GWT system [10–12] for pipes which were commercialised [13, 14] and rapidly adopted by the Oil and Gas industry. Worlton [15] and Viktorov [16] originally explored the potential of UGW for NDT of plate-like structures. Based on this, Mažeika et al. [17] studied the potential for GWT of tank floors.

2.1 Ultrasonic guided waves

Rayleigh waves [16] are surface waves that exist in half-space, a surface backed by a semi-infinite volume. These waves have an elliptical vibration with the major axis of vibration perpendicular to the direction of propagation. They can penetrate to a depth of 1.5λ below the surface. In contrast, Lamb waves fill the entire volume of the plate provided its thickness is less than 2λ . These waves were first analysed on plates by Horace Lamb [18] and can be considered as Rayleigh waves bounded by two parallel surfaces. In plates, there are three fundamental wave modes in the operating frequency range for GWT: namely, the fundamental Symmetric Lamb mode, S_0 , the Asymmetric Lamb mode, A_0 , and the Shear Horizontal (SH) mode, SH_0 , as illustrated in **Figure 2**.

Just like plates, hollow cylindrical tubes also have a thin cross section bounded by two surfaces. Lamb wave theory of plates assumes an infinite plate extent, whereas in cylinders, the circumferential curvature results in a periodic boundary condition in one dimension. This increases the complexity of Lamb waves in tubes, and many more modes of wave propagation occur in tubes than in plates. In pipes, three

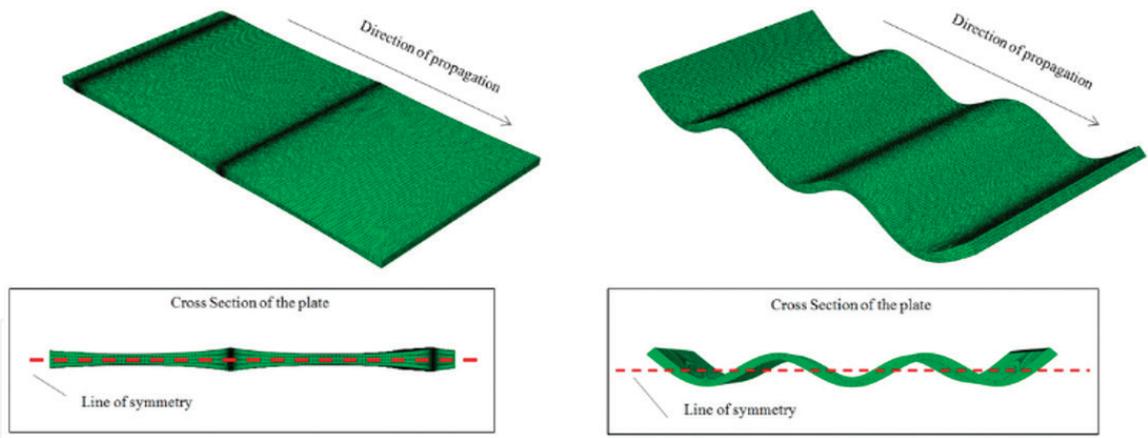


Figure 2. Displacement of the fundamental symmetric (S_0) and asymmetric (A_0) wave mode. Note the displacement from the line of symmetry (red dashed line).

families of modes based on their displacement patterns are present. Axially symmetric wave modes—Longitudinal (L) and Torsional (T); and non-axially symmetric—Flexural (F) modes are illustrated in **Figure 3**. The L and T modes in cylindrical structures are analogous to the Lamb waves and SH modes of vibration in plates, respectively. The wave mode designation is defined by Meitzler [19] and includes two numbers, for example $L(0,1)$, where the first number is the circumferential wave-number (also known as the order) and the second number represents the sequential mode. All axially symmetric torsional and longitudinal modes are zero order modes. Flexural modes are non-axially symmetric and of order higher than zero.

Phase velocity (v_p) and group velocity (v_g) are two important terms in UGW propagation. v_p is the speed at which a continuous wave propagates. For GWT, it is important to discriminate propagating wave modes by exciting them as a discrete wave pulse with a finite number of cycles. This pulse is controlled by a window function (e.g. hamming) which comprises a bandwidth of frequencies. The speed at which this envelope of discrete pulse propagates is v_g . Variation of phase velocity with frequency leads to dispersion occurring as the UGW propagates in the structure.

At any given frequency, a number of wave modes may be present in the structure. The wave modes with frequency dependent velocities are called dispersive as they spread in space over time. Dispersion curves illustrate guided waves and their behaviour with frequency for each possible mode in the given structure. Commercial software packages [20, 21] are available to generate dispersion curves for multi-layered plates and cylindrical structures. **Figure 4** shows the dispersion curves computed for a 6 inch Schedule 40 pipe (168.3 mm outer diameter, 7.11 mm wall thickness) and a

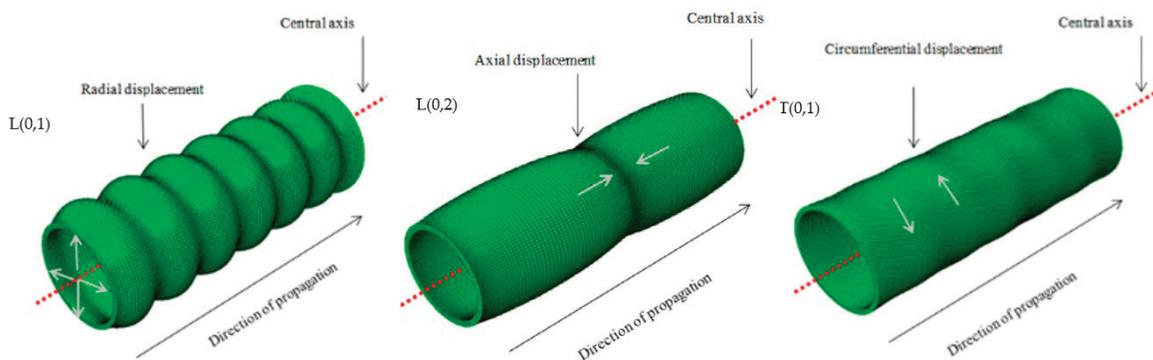


Figure 3. Displacement of the axisymmetric $L(0,1)$; $L(0,2)$ and $T(0,1)$ wave modes. Note the dominant radial, axial and circumferential displacements from the central axis, respectively.

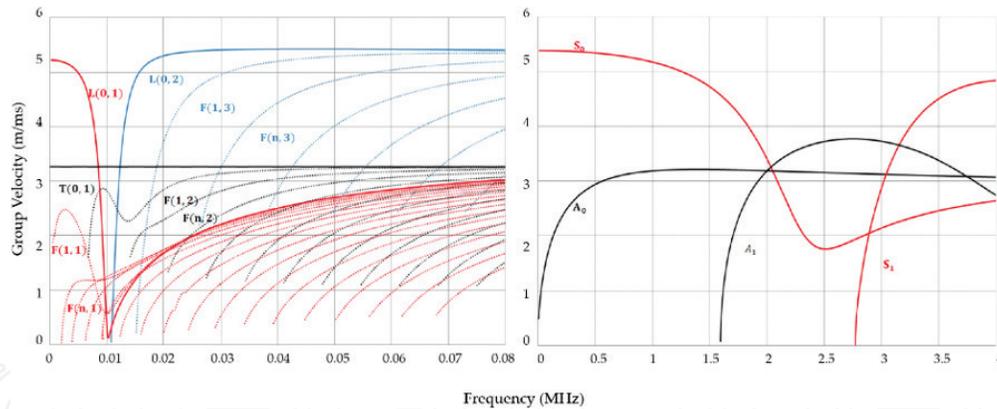


Figure 4. Dispersion curves for 6 inch schedule 40 steel pipe (left) and 1 mm thick steel plate (right); showing the relationship between group velocity and frequency for different modes.

1 mm thick steel plate [material properties used, density (ρ)—7830 kg/m³, Young's modulus (E)—207 GPa and Poisson's ratio (μ) = 0.3].

For the pipe, axisymmetric L(0,1), T(0,1) and L(0,2) modes are highlighted and their respective associated flexural modes, F(n,1), F(n,2) and F(n,3) are coloured red. It should be noted that L(0,2) and T(0,1) in pipes are analogous to A0 and SH0 wave modes in plates. It can be seen that the T(0,1) wave mode is completely non-dispersive for all frequencies of interest for GWT as the phase velocity dispersion curve is flat. L(0,2) is relatively non-dispersive above a certain frequency and L(0,1) is relatively dispersive in comparison to the other two axisymmetric modes. Compared to a pipe, relatively low numbers of modes are present in plates, which makes mode separation and signal interpretation much less challenging. For GWT, it is desirable to use non-dispersive wave modes for easy data interpretation.

2.2 Guided wave excitation

In contrast to conventional ultrasonic testing (UT), where high frequencies are used to examine the material directly under the test location, in GWT, low frequency ultrasound is guided through the structural boundaries and can travel tens of metres. A transducer can excite all modes that exist within its frequency bandwidth and this can complicate the received signals, making their interpretation difficult. Dispersion and the presence of multiple guided wave modes are the two main problems for GWT [22], and for practical applications, it is important for the transducer system to excite a single, non-dispersive wave mode [23]. A procedure for identifying suitable modes for a particular inspection task has been proposed by Wilcox [24] which considers the properties of the structure (dispersion, attenuation and sensitivity) and transducer (excitability, detectability and selectivity).

There are a number of different transduction technologies for excitation and detection of UGW, including Electromagnetic Acoustic Transducer (EMAT) [25], magnetostrictive devices [26], laser [27], piezoelectric and piezocomposite transducers [28]. Piezoelectric transducers offer the most promising solution due to their stability and reliability, and cost-effectiveness with simple and light-weight construction [29]. Lead zirconate titanate (PZT) has been a popular choice for UGW as it shows good electromechanical properties (electromechanical coupling, $k > 0.7$) which is essential to achieve large coverage. Linear and circular PZT arrays on plates have achieved inspection range of 3000 times the dimensions of the array. Application of PZT material is however limited to temperature below $\sim 150^\circ\text{C}$ ($1/2 T_c$) above which it experiences accelerated performance degradation over time [30]. Piezoelectric materials for SHM at higher temperatures are available [31, 32] for steamlines.

For pipes, excitation of axisymmetric wave modes [L(0,2) and T(0,1)] using piezoelectric transducers requires a circumferential ring of transducers. The circumferential spacing between the transducers in the array should be even for a high level of mode purity. All transducers in the ring are excited equally and concurrently to launch these axisymmetric modes. Apart from being non-dispersive, both of these modes provide uniform stress over the whole pipe cross section area and provide 100% coverage. Two rings of dry-coupled piezoelectric shear transducers [33] can be used to obtain unidirectional propagation of the L(0,2) mode with propagation distances approaching 50 metres. The second axisymmetric mode, L(0,1), is excited alongside L(0,2) (**Figure 5**), and can complicate the interpretation of results [34]. Therefore, an additional ring of transducers is required to suppress this undesired L(0,1) mode. This however adds to the cost of the system, significantly for larger diameter pipes. On the contrary, the T(0,1) mode is the only axisymmetric torsional mode in the frequency range of interest for GWT, so to obtain a single mode and unidirectional excitation, only two rings of transducers are required. The torsional mode requires an excitation force in the circumferential direction. This can be achieved by displacing the shear transducer used for axial longitudinal excitation by 90°. To cancel the propagation of non-axisymmetric Flexural modes, the number of transducers in a circumferential ring should be greater than the highest order of flexural mode present in the chosen frequency range [35].

For plates, the A0 Lamb mode is the easiest omnidirectional mode to excite as it only requires a point-source exerting a pure out-of-plane force on the surface of the plate. It is also the mode which has the smallest wavelength for a given frequency, therefore offering better resolution to defects compared to the S0 mode. However, due to the attenuation and higher dispersion characteristics, this mode has been predominantly neglected in favour of S0 and SH0. **Figure 6** shows the propagation of these three modes excited using uniaxial in-plane vibration.

Commercially available in-plane thickness shear transducers can generate all fundamental plate modes in the GWT operating frequency range. Both Lamb modes are generated in the axis of vibration while the SH0 mode is generated perpendicular to the axis of vibration.

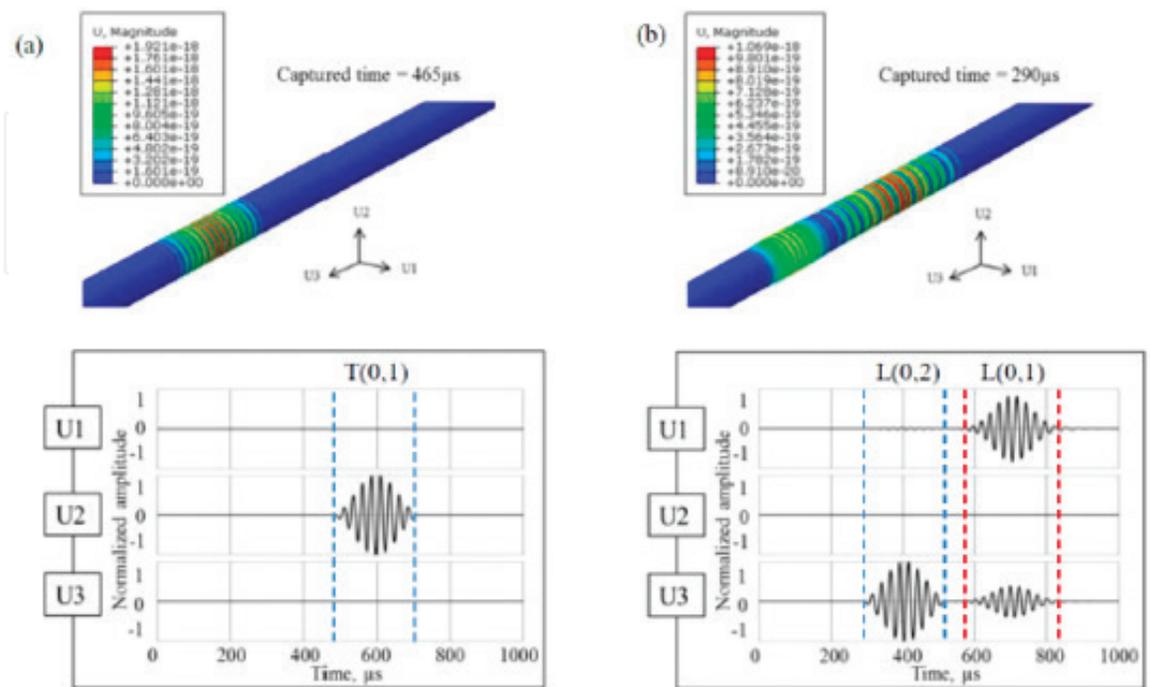


Figure 5. Displacement patterns and waveforms generated by array of shear transducers aligned (a) circumferentially and (b) axially. U1, U2 and U3 represent radial, circumferential and axial displacement caused by transducer vibration measured using a 3D vibrometer.

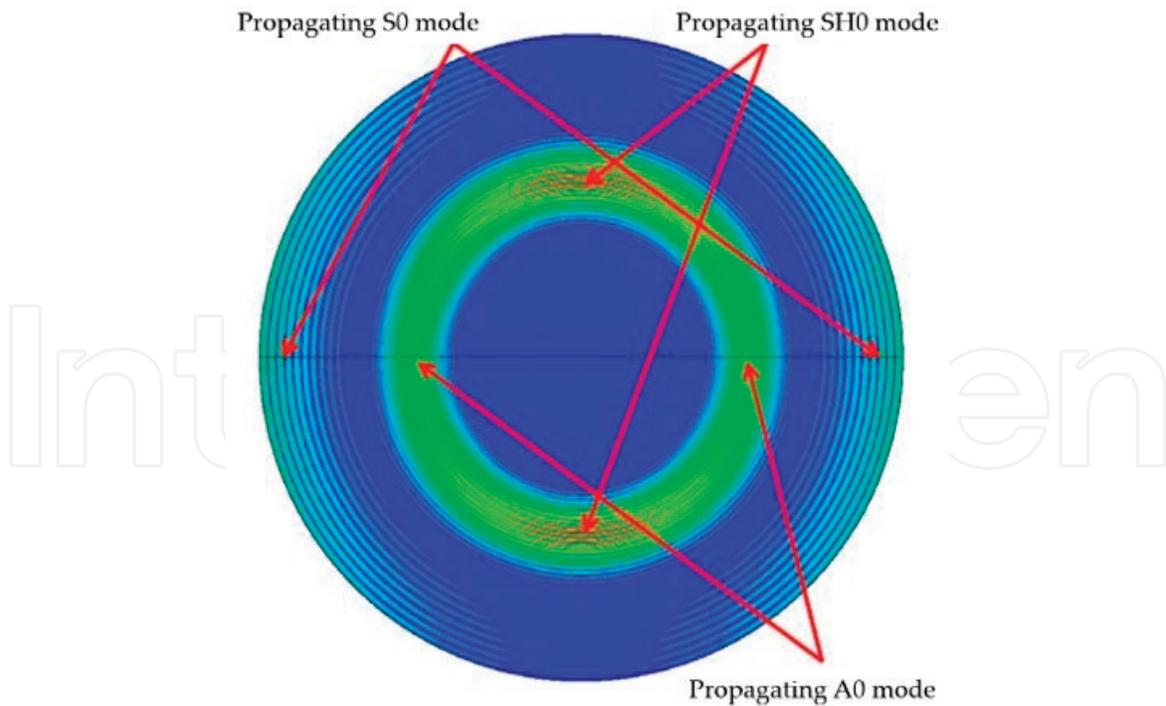


Figure 6.
Propagation of ultrasonic guided wave modes in a 3.5 m diameter, 10 mm thick steel plate from a uniaxial in-plane vibration.

2.3 Guided wave inspection

A typical GWT architecture in **Figure 7** shows the key components of the system. Apart from the transducers, the system comprises of a portable computer (PC) to control the test, and a pulser-receiver connected to the transducers to transmit and receive the ultrasonic signal to and from the structure under test. Narrow band signals such as several cycles of sine wave modulated with a window function (e.g. hamming), are generally used. These narrow band signals offer good signal strength

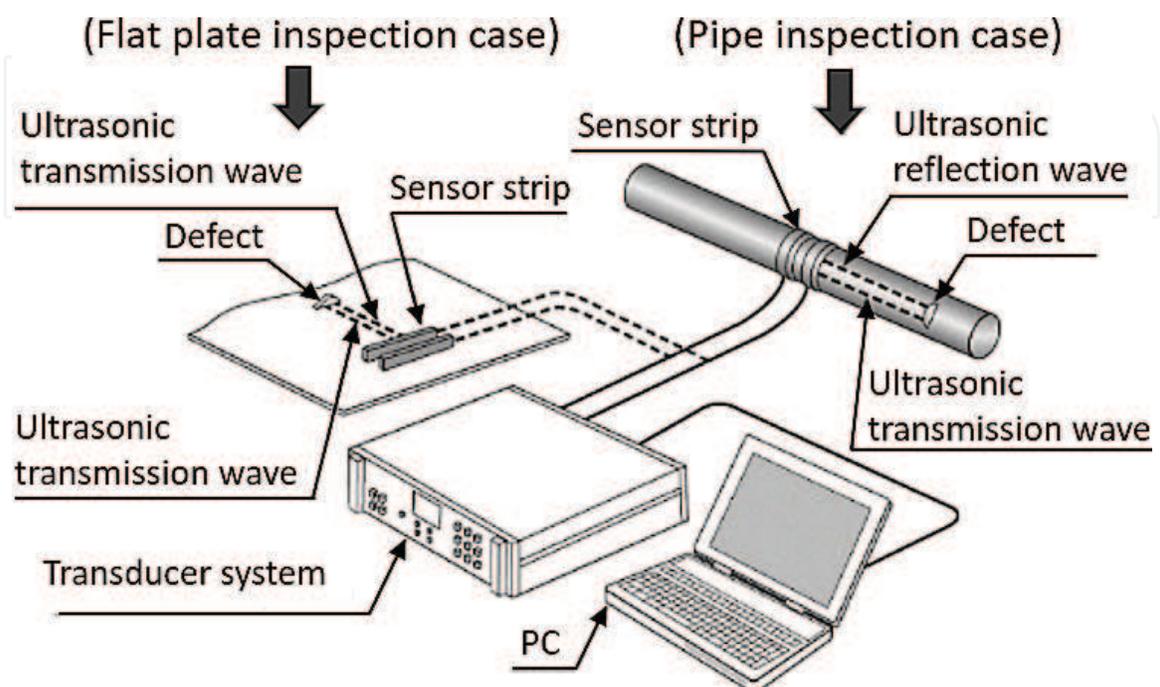


Figure 7.
Architecture of a typical guided wave inspection system [36].

and avoid dispersion while propagating long distances. The centre frequency of these signals are chosen based on the desired wave mode to achieve low dispersion over the frequencies in the narrow band.

There are two modes of operation: pulse-echo and pitch-catch. Pulse-echo mode is more common and utilises the same transducers to excite the UGW and receive the reflected signals as illustrated in **Figure 7**. Pitch-catch mode uses two sets of transducers, one to excite the UGW and the other to receive, and is only used if high resolution or a high inspection range are required. As the UGW propagates in the structure, a proportion of the energy contained in the propagating wave front will be reflected when an acoustic impedance change occurs at a feature or discontinuity in the structure. This enables full coverage of the cross section of the plate or pipe, detecting and locating both internal and external defects without disrupting operation.

Since the initial developments of GWT of pipes in late 1990s, several studies have been carried out to understand the interaction of $T(0,1)$ and $L(0,2)$ guided wave modes with pipe features (flanges and pipe supports) [37] and defects [35], and the effect of different defect characteristics and excitation frequencies has also been reported [38, 39]. This has led to definitions and standards for GWT instrumentation, data collection and analysis in ISO 18211:2016 [40]. When an axisymmetric mode is incident on an axisymmetric pipe feature such as a uniform weld or a flange, axisymmetric modes are reflected. With a non-axisymmetric feature such as corrosion, a non-axisymmetric wave will also be reflected back to the transducer array. The presence and axial location of defects can thus be determined by analysing these reflections and their time of arrival. Although the $L(0,2)$ mode has shown ~ 2.5 times more flaw sensitivity compared to $T(0,1)$ [34], it is difficult to excite in pure form and requires complex signal processing due to its dispersive nature. It is also affected by fluid in the pipe, so the torsional mode is more commonly used in practice. GWT using $T(0,1)$ is most effective on straight sections achieving several tens of metres of inspection range but recent studies have evaluated its performance on bends [41].

3. Structural health monitoring

The desire to move from current periodic structural maintenance to a more cost-effective condition-based maintenance (CBM) philosophy to ensure integrity of critical structures has fostered research and development activities to develop SHM solutions. SHM using UGW has found a variety of practical applications for elongated engineering structures including pipes, plates, ship hulls, rails and cables, because of its inherent long range propagation [42].

3.1 Monitoring system design and architecture

The operational requirements of SHM systems for pipelines and storage tanks are tabulated in **Table 1**. Currently, costly acquisition of SHM data is only justifiable for structures with significantly high failure consequences. Transducer technologies play a critical role in the design of SHM system as they are permanently installed on the structure and required to repeatedly transmit excitation signals and analyse the received responses.

The transducers may need to be attached in environmentally hostile, safety-critical or difficult-to-access areas and therefore they should be designed to perform reliably under prolonged exposure to harsh environmental and operational conditions (EOCs). Therefore, low cost and reliability are the two main factors to consider when designing a SHM sensor system for pipelines and storage tanks. One

Operational requirement	Pipelines	Storage tank floor
Operating temperature	-10 to 150°C	-10 to 60°C
Signal to noise	<6 dB	<6 dB
Operating frequency range	20-100 kHz	Resonant frequency
Transmission range	Up to 100 m	30-100 m
Frequency of data collection	Once a week	Once a week (depending on the condition)
Wave mode selection	T(0,1)	S0 and SH0
Signal processing	Thresholding/outlier analysis Baseline subtraction Pattern recognition	Tomography Pattern recognition Neural networking Baseline subtraction
Data acquisition	Pulse-echo/pitch-catch	Pitch-catch

Table 1.
Operational requirements of SHM systems.

cost-effective approach is to use a single pulser-receiver and PC to collect monitoring data from multiple sensor locations at junction points, which can be located in easily accessible location. This significantly reduces cost of repeated access and of the overall system.

3.2 Monitoring system for pipelines

Current state-of-the-art in pipeline monitoring solutions includes corrosion coupons, acoustic emission and magnetostrictive sensors, flexible eddy current arrays, flexible ultrasonic transducers, guided wave sensors, impedance spectroscopy, microwave backscattering and fibre optic sensors. A review of these monitoring technologies can be found in [43]. Corrosion sensors based on electrical resistance and electromechanical impedance spectroscopy can only provide coverage over a small area and are not suitable for non-uniform corrosion artefacts such as pits. Recent advances in acoustic emission (AE) sensor technology [44, 45] have led to corrosion detection and monitoring solutions where acoustics signals from micro-fractures and delamination of the oxide are analysed. These emissions release much less energy than emission from crack growth where AE has shown great potential. In low noise environments AE could be used to detect signals from corrosion with tens of metres range using monitoring frequencies of tens of kilohertz. However, in a live plant, high process noise requires several hundred kilohertz of monitoring frequencies and coverage is limited <0.5 m and requires complex signal processing. For this reason, AE is limited for this application. Magnetostrictive sensor (MsS) is another technology for pipeline monitoring first developed and patented by SwRI[®] [46]. They have lower power output compared to piezoelectric transducer, however, recent advancements have reported significant improvements in their power output, sensitivity and flaw characterisation [47]. Piezoelectric sensing offers the most promising solution due to their stability, reliability, and cost-effectiveness as described in Section 2.2. This has enabled the development of several SHM solutions. Guided Ultrasonic Ltd. offers one such monitoring system gPIMS [48] and this system's stability and defect detection capabilities have been demonstrated [49] at temperatures up to 90°C. Another example is the system developed by the authors and its installation,

operation and performance is reported [50]. **Figure 8** shows some of these pipeline monitoring devices.

3.3 Monitoring system for storage tanks

Monitoring of a tank floor is more important compared to the tank wall, due to the fact that degradation of the tank floor is not visible until it becomes severe. A tank floor comprises a large number of plates (dependent on the tank diameter) of 6–8 mm thickness joined with lap welds. SHM of tank floors using UGW is challenging due to this complicated layout, the propagation distance requirement, level of attenuation, and wave reflections and mode conversions at boundaries. GWT of above-ground storage tanks (AST) is an emerging technology and was first explored in 2006 by Mažeika et al. [17]. S0 mode was chosen as the principal mode of interest due to low energy losses from the fluid inside the tank compared to A0 mode [51]. Considering the large area and complexity of tank floor designs, guided waves should be transmitted with as much energy as possible. To achieve full coverage, a Pitch-Catch configuration (through transmission) is preferred for data acquisition and the appropriate transducer array layout was studied by Mažeika et al. [17] and Feng et al. [52].

Transducer bonding is also problematic as the tank annular chime gets heavily corroded over time due to environmental influences. Previous studies on selection of sensor location have evaluated two scenarios: wave excitation on tank annular chime; and tank wall. Currently, normal mode transducers (elongated type) are installed on the annular chime of the tank to transmit guided waves across the floor plate, and a tomographic technique is used to map the structural health of the tank floor [53]. The SH0 mode is an interesting alternative to the S0 mode for this application due to its non-dispersive characteristic [54]. Advances in flexible shear mode transducers led to a recent study [55] on their application to SHM of AST floors. This study evaluated the two modes of interest: S0 mode for normal excitation; and SH0 mode for shear excitations. Sensor location on both the tank wall and annular chime were considered for the two modes. The sensor location is illustrated in **Figure 9**.

The wave propagation for both cases is illustrated in **Figure 10**. A significant amplitude drop for the applied normal load on the tank wall was observed in comparison to the tank floor. However, in the case of shear loading, insignificant amplitude drop was observed.

The application of shear stress on tank wall for guided wave testing of tank floors was thus realised. This increases the potential market for tank floor inspection using UGW as the tank wall can be used to bond shear transducers for structural health monitoring.



Figure 8. Commercial pipeline SHM systems (left to right): MsS [46], gPIMS [48] and iPerm [50].

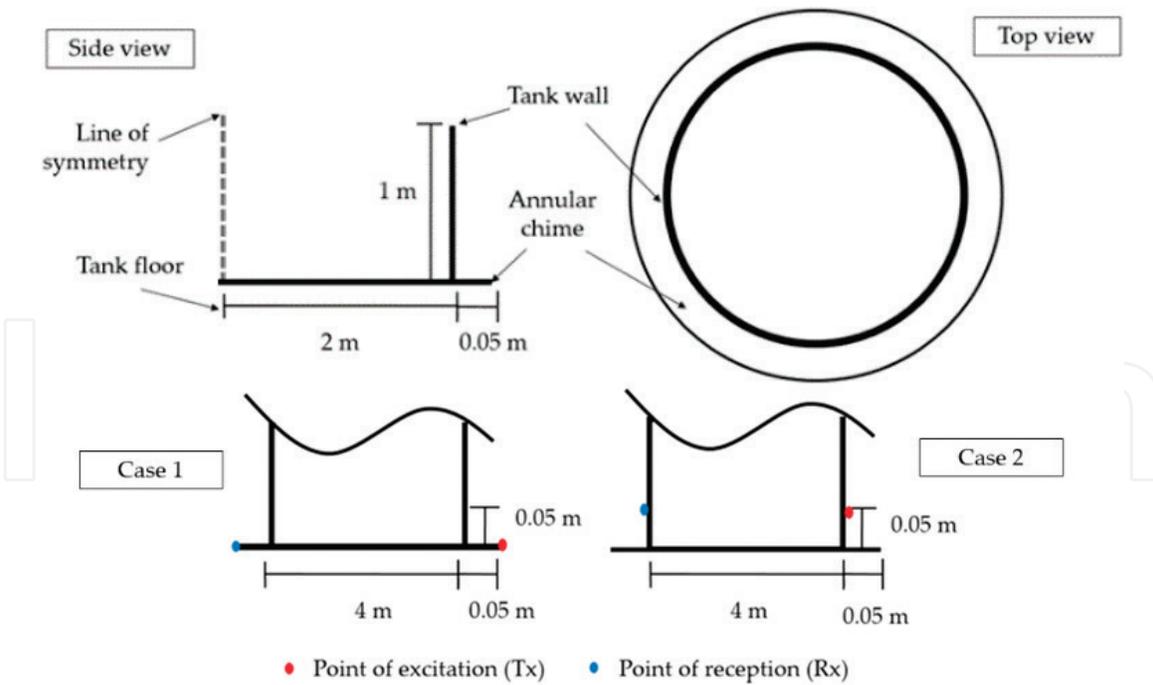


Figure 9. Schematic of a tank (top) and layout of the point of excitation and reception of the two cases studied (bottom)—excitation and reception from the tank floor in Case 1 and tank wall in Case 2.

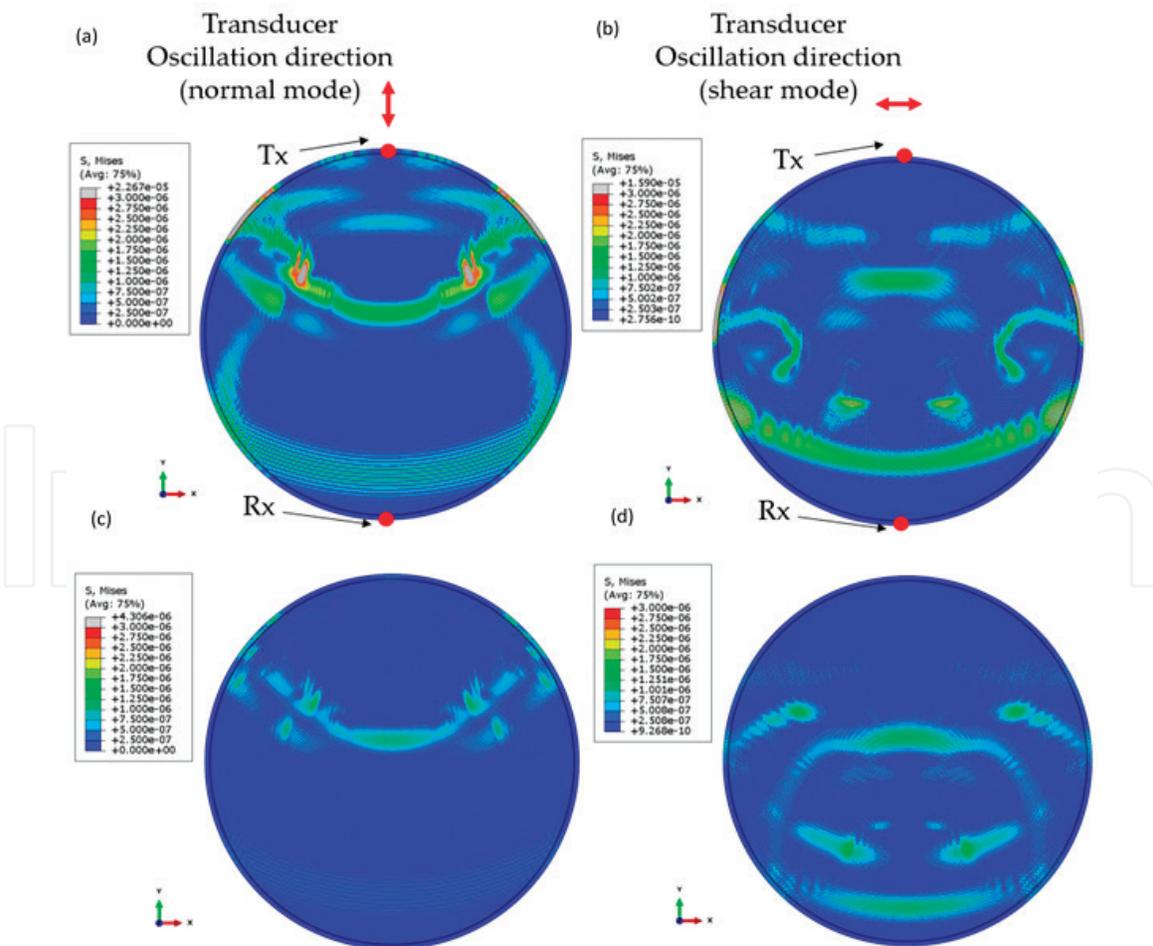


Figure 10. FEA showing UGW excitation on tank annular chime and tank wall: applied (a) normal and (b) shear stress on tank chime; and (c) normal and (d) shear stress on tank wall.

4. Data processing for SHM

4.1 Effect of environmental and operating conditions

Several investigations into the effect of environmental and operational conditions on the recorded ultrasonic signals have been carried out, and change of temperature has been shown to be the main source of signal fluctuations [56–58]. The influence of temperature on GWT is a combination of effects due to the structure's mechanical properties and the effects on ultrasonic transducers and their bonding. Previous study has reported that, for small ambient temperature variations of a few degrees, the effect on transducer performance is much less significant than that on the wave propagation [59]. The UGW signals will undergo changes in the amplitude and phase. The change in UGW signal amplitude is attributable to changes in temperature-dependent properties of the ultrasonic transducer, particularly the piezoelectric materials and adhesives. To minimise this variability, careful selection of adhesives and transducer material for target temperature is recommended. The phase shift in the UGW signal is due to the change in wave propagation velocity due to variation in the mechanical properties of the waveguide [60], i.e. pipe or tank floor in this study. The material properties of relevance include elastic and shear moduli, and the density; which in turn relates to the elasto-acoustic properties of the material, acoustic absorption and ultrasonic wave velocity. Thermal expansion adds to this effect by changing the propagation distance directly and indirectly through changes in the thickness of the plate or the pipe. The relationship between the difference in time of arrival (TOA) of the signal and the change in temperature of the structure can be described as:

$$\delta t = \frac{d}{v}(\alpha - \gamma)\delta \quad (1)$$

where δt is the difference in TOA of the signals when the change in temperature of the structure is δT . d is the distance travelled by the wave and v is the wave velocity. α is the coefficient of thermal expansion and γ is the coefficient of change in phase velocity. γ is generally much greater than α and hence from Eq. (1), it can be seen that the main contribution to change of TOA is from change in wave velocity due to temperature variations. Also, since the time shift is directly proportional to the propagation distance, it can be noted that the effect of temperature on UGW will increase with propagation distance. This can be significant for the large propagation distances required for pipes. The inverse relationship between temperature and wave velocity suggests that faster modes will be less affected than slower ones. These temperature induced variations in UGW signals can adversely reduce the defect detection capabilities of the SHM system. An experimental study [61] showed that the effect of temperature variation on UGW from ambient temperature up to 70°C was much more pronounced than the effect of a drilled hole of 1 mm diameter.

4.2 Temperature compensation algorithms

The issues described in Section 4.1 led to several investigations within the SHM research community and a number of EOC compensation strategies have been proposed. Their main objective is to achieve UGW propagation time and amplitude correction for enhanced defect sensitivity. These correction strategies can be classified into two techniques: data-driven and analytical physics-based.

The data-driven techniques requires a large set of baseline measurements from the structure at different temperatures. A signal from the 'bank' of baselines is then selected to minimise the difference relative to the test signal for a particular temperature. This method is called Optimum Baseline Selection (OBS). A number

of selection criteria including mean square deviation [56] and maximum residual amplitude [62] have been proposed. This method has limitations for cases when a large set of baselines is not available and if the temperature of the selected baseline is different from the temperature of the test signal. Baseline signal stretch (BSS) was introduced as a complimentary technique that in its simplest form requires only one single baseline at a reference temperature. In BSS, time domain stretching is performed to adjust the selected baseline and the local coherence is estimated as a function of time. BSS can be performed in both time and frequency domain to achieve similar performance [63]. A number of researchers have explored these methods to provide enhanced temperature compensation with a reduced number of baseline data sets [62–65]. The temperature resolution of the baseline set is defined by the capability of BSS method as the stretching required for large temperature difference leads to distortion of the signal's frequency content. The performance of BSS depends on signal complexity and mode purity and. For practical application, a temperature step of 1–2°C is recommended for baseline dataset [63]. Recently developed modified-BSS (MBBS) method outperformed BSS and is more effective for temperature differences of up to 13°C [66]. BSS can be computation intensive and alternative methods with improved computational speed have been proposed that operate on signals in the stretch factor and scale-transform domain [67].

Physics-based analytical techniques for temperature compensation [68, 69] utilise underlying physical principles such as changes in material properties and thermal expansion (described in Section 4.2) for transducer signal reconstruction at different temperatures. The advantage of these techniques is that it does not require a large set of baseline sensor measurements from the structure. The performance of these analytical temperature compensation models is shown to be at par with the state-of-the-art data driven techniques. They are however limited to simple structural geometries and boundary conditions. Combinations of analytical and data-driven strategies that require fewer baselines are being explored [70] which will offer an efficient, practical and useful approach for temperature compensation.

4.3 Damage detection strategies

A method for damage detection must be applied to the corrected data to see whether the structure being monitored has developed any damage. In structures containing high densities of structural elements, the time-traces obtained are often too complex to be directly interpreted due to a large number of overlapping reflections. A popular approach for SHM is *baseline subtraction*, which is based on the comparison of structure's ultrasonic response at original state (baseline) with response at a later stage. The subtracted *residual signal* will remove reflections from pipe or tank floor features and isolate any damage scattered signals as illustrated in **Figure 11**.

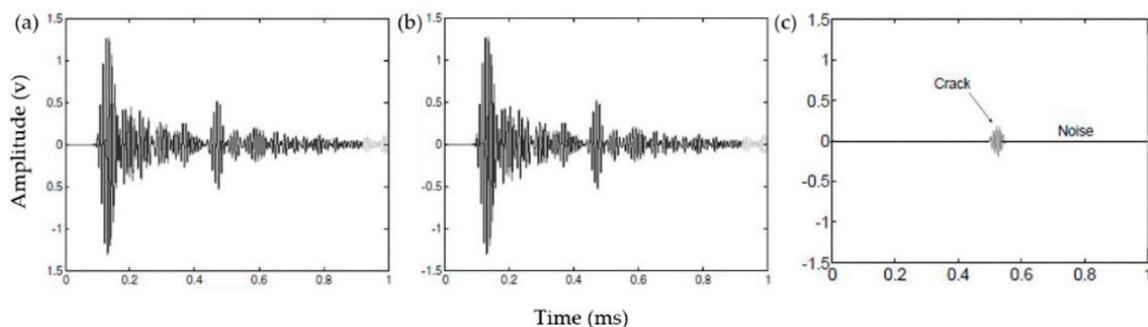


Figure 11. Baseline subtraction of UGW time traces (a) undamaged structure (b) damaged structure (c) defect signal after baseline subtraction [71].

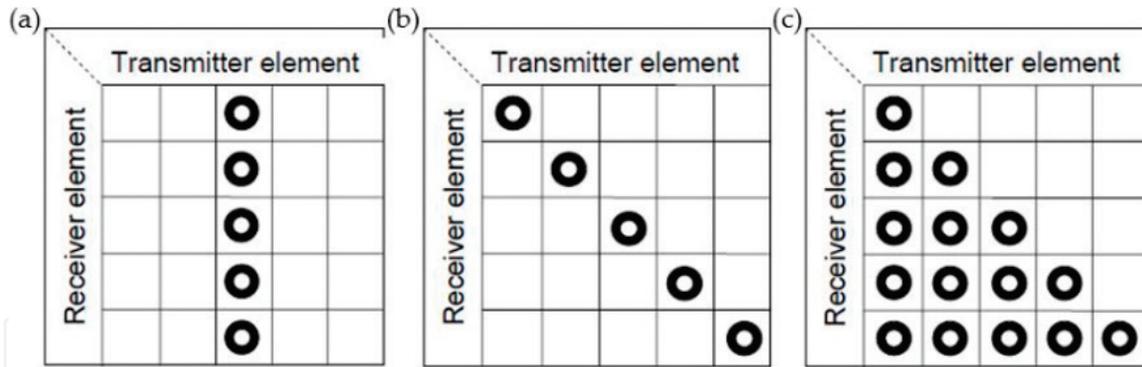


Figure 12. Transmit-receive matrices for the imaging algorithms; (a) common source method (b) synthetic aperture focusing technique and (c) total focusing method [72].

For sensor arrays Full-Matrix Capture (FMC) is a data acquisition process which records all possible transmit-receive combinations of UGW data. This data collection matrix is symmetric due to reciprocity (**Figure 12**) and only the lower and upper triangular parts of the matrix need be recorded. This data can then be used to obtain tomography images of the structure or perform sound energy focusing techniques to improve SNR.

For complex structures and if the data corresponding to the damage state is not known *a priori*, damage detection strategies based on unsupervised algorithms are used. One such strategy is based on the Outlier Analysis (OA) algorithm which extracts damage sensitive features from the UGW signals and aims to identify if they have deviated from their baseline distribution using Mahalanobis squared distance [73]. OA can be applied as univariate and multivariate depending on a number of features. For univariate implementation, root mean square (RMS) of the signal has been successfully used as a damage sensitive feature for detection of corrosion type defects in plates [56] and pipes [74]. To increase the damage sensitivity, multivariate OA is recommended, where a number of features are extracted from the UGW signals and classical methods of multivariate statistics such as principal component analysis (PCA) are applied. For UGW, the features of interest include time-of-flight, frequency centres, energies, modes of scattered waves, and time-frequency spread. A review of the feature extraction approaches based on time-frequency representations such as short-time Fourier transform, Wigner-Ville distribution, Hilbert-Huang transform, and wavelet transform can be found in [75]. Recent advances in the field of artificial intelligence led to researchers formulating defect detection as a machine learning problem. A study using an Artificial Neural Network (ANN) based strategy was applied for damage classification [73] and was reported to outperform OA for damage detection using just one feature. Such supervised machine learning strategies will however require data from the structure with known types and levels of damage, which may not always be present.

5. Conclusions

This chapter presents the advances in guided wave technology for structural health monitoring of two of the most critical metallic assets, pipelines and storage tanks, in the Oil and Gas industry. These SHM technologies support cost-effective asset integrity management by enabling a condition based maintenance model, moving away from conventional routine inspection. The advances in SHM technologies of pipes and tanks are presented. Operational requirements of these SHM systems

are discussed with a thorough review of the state-of-the-art and fundamentals of pipelines and tank floor inspection using UGW. Limitations of SHM for high temperature pipelines have also been identified for future research and development.

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