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Inspection and monitoring for life-cycle management of natural gas pipelines

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Abstract

As natural gas pipelines consist significant lifelines for the industrialised society, their safety and reliability against various man-made and natural hazards at any point in time are of great importance. This review paper is an overview of typical earthquake-induced damage scenarios and failure modes of natural gas pipelines, as well as different state-of-the-art technologies that are currently implemented for inspection and monitoring. As different elements of a pipeline have various structural typologies, respective inspection and monitoring technologies are diverse as well; their choice being always related to the specific objective of identification.

Methodologies which use recorded data measured along a pipeline for operational control, structural failure risk assessment and life-cycle management are put into context with approaches of multiple criteria and multi-objective analyses that can be used in decision making, taking versatile technical, financial, environmental and societal aspects into account. The paper concludes with a critical discussion regarding the pros and cons of different inspection methodologies, limitations and challenges to be met.

1 Introduction

Natural gas pipelines are extensive lifelines that transport gas over distances of thousands of kilometres through regions with varying soil, site and geological conditions. The exposure of pipelines to various environmental threats such as humidity, chemical properties of surrounding materials, extreme temperatures and operational influence, contamination of gas and high pressure or fatigue loading can lead to health deterioration due to corrosion or damage. Typically these long-term processes can result in local failure, which becomes apparent as leakage.

Apart from deterioration that develops usually over long periods, pipelines can be affected and severely damaged by external events such as earthquakes, landslides, flooding, sea bed movement or man-made impacts (i.e., excavation injuries). In figures 1 and 2 the numbers of incidents that were identified as significant by the U.S. Pipeline and Hazardous Materials Safety Administration (PHMSA) between 2005 to 2015 are shown for the U.S. gas distribution and transportation network.

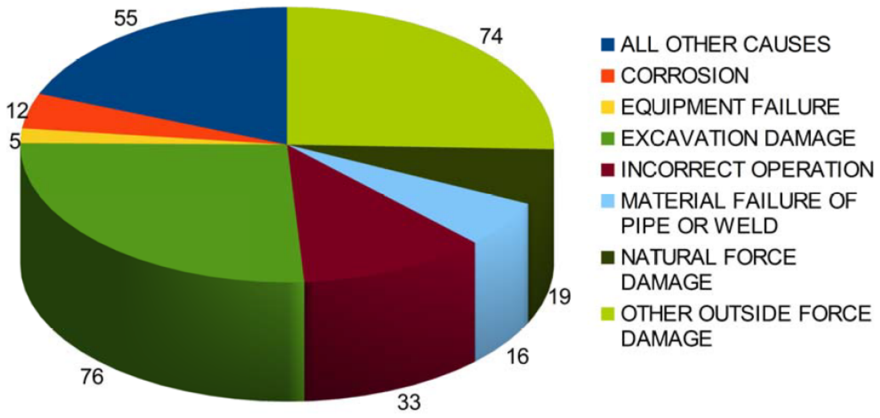

Figure 1: Serious incident rates and causes in the U.S. gas distribution network from 2005 to 2015: data source: U.S. PHMSA data base, 17th Oct. 2016

A comparison with older statistics [77], [5], [60] shows different distribution of the various causes of incidents, however, overall, the absolute number of significant incidents shows a decreasing trend.

The statistical data presented in figures 1 and 2 refer to the number of incidents neglecting the respective consequences. Recent studies have shown though, [51] that even though incidents caused by natural hazards are relatively rare, they cause 34 % of all property damage of pipelines as, for instance, pipe rupture can be far more severe than corrosion-induced leakage.

The majority of natural gas pipelines are expanded outside of urban areas, typically within a remote environment, thus hindering the reliable damage identification or tracing of the conditions that can lead to further deterioration. Some of the most essential requirements that need to be satisfied by respective equipment for large scale monitoring and inspection are:

- Acquisition of information about the pipeline's state over long distances without human intervention,
- High degree of resistance against harsh environmental conditions,
- Minimal interference of function of the pipeline and
- Sufficient precision of the measurements.

Data to be acquired by any technical device in-situ has to be processed and interpreted such that respective decisions about possible repair, interruption

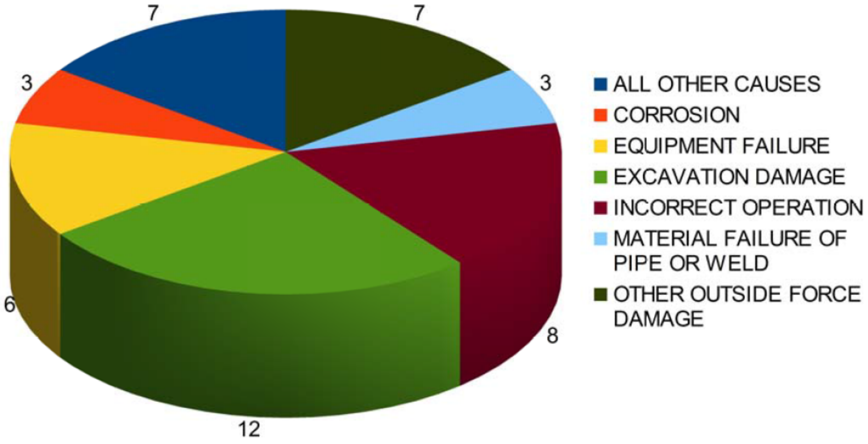

Figure 2: Serious incident rates and causes in the U.S. gas transportation network from 2005 to 2015: data source: U.S. PHMSA data base, 17th Oct. 2016

of service or maintenance can be derived. In this context, the main criteria to be addressed are the maximum probability of detection of a certain damage and the minimum probability of false alarm. Furthermore, tools have to be provided that allow the operators to decide within short time about the need for immediate shut-down and/or appropriate measures of repair. In this context, monitoring and inspection serves the optimisation of maintenance scheme.

Natural gas pipeline systems consist of several components that need to function interactively to provide a reliable and stable transportation of gas from the storage stations to the end-consumer. These components encompass:

- *Transmission pipes*: Mainline pipes are usually of 80-150cm in diameter, while pipes delivering gas to or from a mainline have smaller diameters of 15-60cm. Transmission pipes consist of carbon steel that needs to satisfy specific national and international standards. Highly advanced plastics are also often utilised in distribution networks.

- *Compressor stations*: To ensure that the gas remains highly pressurised during its transportation, periodic compression of the natural gas is required. These stations are commonly located at intervals of approximately 100 to 200 km along a line. Apart from being pressurised, natural gas is often dehydrated and filtered in compression stations.

- *Metering stations*: Between compressor stations, additional metering stations are designed along a pipeline to measure the gas flow.

- *Valves*: To allow the shutdown of sections of a pipeline for maintenance purposes, repair or replacement, valves are placed at distances of several kilometres.

- *Control stations*: All data that is monitored along a pipeline is processed in central control stations from where the pipeline network is operated. For this purpose, data transmission lines are installed along the pipelines, to collect measurements from compression and metering stations. The components for the communication and data acquisition that provide the information about the service of a pipeline to the control stations form Supervisory and Data Acquisition (SCADA) systems.

In this review paper, several techniques for inspecting the structural integrity of gas pipeline systems are presented, involving long-term environmental and operational effects and natural hazards such as earthquakes or landslides, that can lead to exceedance of different damage states of the pipelines. After a summary of typical defects and damage modes, different technical solutions are discussed. Given that the data acquired by means of monitoring inspections is incorporated into risk assessment and risk management of pipeline systems, section 4 is dedicated to schemes and methods which developed to support informed decision-making by the gas network stakeholders.

2 Defects and damage modes to be detected in pipelines

Prior to developing a strategy for monitoring and inspecting a pipeline system, strength degradation and damage modes, as well as the respective severity of damage as per the operation of the system need to be first defined. Assuming normal operation of a pipeline network, there are different mechanical phenomena that can lead to the ultimate limit state. These phenomena are effectively targeted by appropriate inspection and/or monitoring techniques and are listed as follows:

- Corrosion,
- Third party (i.e., man-made) damage such as excavation,
- Fatigue and other cracks,
- Material and/or construction defects,
- Ground movement, e.g. due to landslides, flows and earthquakes,
- Leakage.

2.1 Corrosion

Corrosion is an oxidation of metal that is caused by chemical reaction of the material with a second element [31]. It has to be considered as one of the major sources that causes deterioration in natural gas pipeline systems. In general it is distinguished between internal and external corrosion.

External corrosion is the chemical reaction of the steel pipe with its surrounding environment. In case of buried pipes, the surrounding material is soil. Submarine pipelines are surrounded by sea water when deployed on the sea bed.

As natural gas can be contaminated by small amounts of water or other corrosive substances, corrosion can be provoked from inside a pipe as well. This process is called internal corrosion.

In both cases, the thickness of the pipe is reduced and this results into loss of strength and subsequent cracking, leakage or, ultimately, rupture. Therefore, the respective detection methods mainly rely on the identification of changes of the wall thickness.

Detection and mitigation of pipeline corrosion is a subject on which very much research and industrial development has been carried out in the previous decades. Several studies have been described in the literature, focusing on the description and numerical modelling of corrosion [38], [72], [42], its detection [49], [53], [14], [13] as well as its evaluation and reduction, for both the cases of internal and external corrosion [45], [77], [21], [38], [69] and [70]. Several of these topics are further covered in more general guidelines and publications such as [5], [7], [19] and [31].

2.2 Excavation damage

In case that the soil covering a gas pipe is excavated without due consideration, damage can be triggered ranging from insuring the corrosion protection of the pipe to rupture. In the U.S. alone, 1630 pipeline incidents due to third-party excavation were reported by PHMSA [60] within 1993 to 2012. Note that third-party refers to excavations that were not carried out by the operators of the pipeline or the contractors. This is also supported by figures 1 and 2, where excavation remains one the major sources of damage of buried pipelines. Comprehensive discussions over excavation damage can also be found in [60] and [77].

2.3 Ground movement

Ground movement can be caused by a number of different phenomena, the most hazardous of which are landslides and earthquakes. These actions can cause large (generally static or slowly developing) deformations that can subsequently lead to severe induced strains and rupture. Depending on the pipeline construction technique (i.e., continuously-welded or segmented pipes), the respective failure modes are classified into two groups as presented below [55] based on the reported evidence from the literature and the associated failure criteria.

2.3.1 Damage to continuous steel pipelines

Based on the assumption of a flawless welding process and corrosion-free conditions continuous, welded steel pipelines, five primary, ground movement-induced failure mechanisms are commonly distinguished [84], [55]

- *Pure tensile rupture*: Excessive longitudinal strains due to axial tension can result into pipe rupture. This type of failure has been rarely observed in arc-welded steel pipelines with butt connections as they behave in a ductile manner, however, steel pipelines assembled with gas-welded slip joints are more vulnerable to this failure mode as they have very low tensile capacity. Examples of this failure have been observed after the 1994 Northridge earthquake [56] among others. According to [35], the ultimate tensile strain of X-grade pipe steel at fracture may reach 6%. Nevertheless, in engineering practice a more conservative value of 3% or 4% is applied. For the numerical description of the nonlinear structural behaviour of steel under tension, a suitable material model such as the Ramberg-Osgood model [64] is required.

- *Local buckling*: This failure mode is commonly refered to as *wrinkling*. It is a failure condition that occurs due to structural instability in a pipe under longitudinal compression, often combined with bending. Depending on the extent of the acting forces, this local distortion of the pipe wall can cause further bending and eventually tearing of the pipe. Local buckling has been observed in several pipelines after earthquakes [55]. In most cases, local buckling distortions were accumulated at the regions of geometry transition, such as bends and elbows. For design purposes, a failure criterion for pipe local buckling was proposed in [29] based on experimental studies, defining a critical compressive strain by means of the ratio of a pipe's wall thickness to its diameter. As stated in [55], this criterion is better applicable to thin-walled pipes, but is relatively conservative for thick-walled ones.

- *(global) Beam (upheaval) buckling*: Pipes can also be considered as long slender structures that are prone to global stability failure under longitudinal compression. This geometrically nonlinear behaviour usually results in a global deformation which does not necessarily lead to fracture and is therefore considered as less catastrophic [55]. Beam buckling can usually be prevented by a sufficient cover of overlying backfill soil. In fact, it has been shown [48] that there is a proportional relationship between buckling load and trench depth, i.e., if a pipeline is constructed at a depth larger than a critical cover depth, then local buckling will occur before beam buckling and vice versa. This practically implies that a minimum cover depth of 0.5 to 1.0 m, which is usually satisfied in practice, is adequate to prevent beam buckling, an assumption that has also been proven valid [48].

As beam buckling does not necessarily interrupt the gas flow, its identification requires careful inspection as reported, for example, in [47].

- *Flexural failure*: Due to the high ductility of steel pipelines, flexural failure hardly ever develops. On the contrary, a number of buried gas and liquid fuel pipelines were found after the 1971 San Fernando earthquake to have absorbed approximately 2.5 m of soil displacement in the transverse direction [57].
- *Section distortion*: Severe bending of a pipe can force the pipe to ovalize in a way similar to tunnel ovalisation under seismic excitation, thus risking pipeline serviceability. As ovalization can be quantified as a reduction of the pipe diameter along the direction of the shorter axis, the value of 15% diameter reduction has been identified as the respective threshold to avoid section distortion [28].
- *Damage to pipelines with welded slip joints*: While failure criteria for butt-jointed pipelines are mainly related to pipe material strength, for pipelines with slip, riveted or gas-welded joints, failure criteria have to be formulated with respect to joint strength, since the joints are usually weaker than the main pipe body. A number of studies involved the estimation of the strength of slip joints with inner and outer weld [76] in terms of joint efficiency, namely the ratio of joint to pipe strength. Joint efficiency values in the range of 35-40% [50] and [8] were obtained in all cases. Detailed damage evidence at welded joints exists for the case of the 1971 San Fernando earthquake, where most of the failures were observed at the welds of gas-welded joints.

A more in-depth discussion on the failure modes of continuous steel pipelines as well as recent observations of damage, can be found in

2.3.2 Damage to segmented pipelines

For segmented pipelines linked by means of mechanical jointing or fitting techniques (e.g. bell and spigot, flanged pipe joints), as may be the case with cast iron, ductile iron and concrete pipes, damage due to permanent ground motion appears to be mostly localized at the joints. For instance, following the 1991 Costa Rica earthquake six distinct failure modes occurring in segmented pipelines were identified in field inspections [54]:

- *Axial pull-out at joint*: This failure is most common when the tensile forces in the pipe barrel exceed the shear load capacity of the joints. As a failure criterion with respect to the onset of leakage at the joint-pipe interface in [22] was proposed to limit the joint slip along the contact area to the half of the joint insertion depth. The validity of this threshold value was confirmed by laboratory tests on concrete segmented pipes connected with rubber gasketed joints subsequently [9]. In a more recent numerical and experimental study, considerable allowable longitudinal and rotational deformations were identified for ductile iron water pipes with bell and spigot joints [83].

- *Compressive 'telescoping' at joint*: Compressive failure of the bell and spigot joint pieces has been observed in several cases of severe compressive ground strains [3]. Based on laboratory tests [9] the ultimate compressive force of the concrete, obtained as the product of the compressive concrete strength and the pipe cross-sectional area (was suggested as joint crushing failure criterion for concrete pipes.
- *Disconnection at T-joint*: Tensile forces in one branch that is connected to a T-joint may lead to a slip and disconnection if the shear load capacity of the joint is exceeded.
- *Blowout at T-joint*: If the material strength of a T-joint is exceeded due to restraint forces and/or moments, the fitting body can break.
- *Break in union piece*: As the union piece connecting two pipe sections longitudinally creates an abrupt change in stiffness, this location becomes vulnerable especially under strong flexure. Accordingly, rupture can be provoked at the interface between union piece and regular pipe section under the action of large forces or bending moments.
- *Pipe segment break*: If the stresses in a regular pipe section exceed the strength of its material, cracks can be generated that can eventually result to fracture.

It is worth noting that most of the above failure mechanisms reported for continuously welded and segmented pipelines can in fact develop under permanent ground movement, the latter induced by natural hazards and their subsequent forces. However, as pipelines are also affected by corrosion, construction imperfections and man-made damage, the observed failure may well be the outcome of a number of simultaneously acting phenomena. As a result, health monitoring and inspection have to interpret the coupled effect of multiple phenomena on the serviceability and safety of pipelines in time [4]. The main technologies for inspection and monitoring of such systems are presented below.

3 Technologies for inspection and monitoring of pipeline systems

To ensure continuous function of natural gas pipelines over their lifetime, the control of deterioration and damage evolution is essential. Along these lines, regular inspections and permanent monitoring of pipeline systems consist an important part of the lifecycle management of pipeline networks.

Monitoring of natural gas pipes includes sensing systems that register quantities determining the operation, mainly, flow velocity, pressure and humidity of the gas. Sensing systems are also utilised to assess and control structural integrity. The latter group of structural health monitoring systems include some fundamental requirements [26], namely, (a) nearly real-time health screening, (b) no service interruption during the monitoring process, (c) continuous capturing of variations in specific metrics that determine the state of the structure, (d) transmission of acquired data through an established, secure and sustainable wired or wireless network and (e) data analysis aiming to detect and assess damage patterns, location and extent. It is also noted that current SHM techniques do not only offer a broader insight of the structure's integrity in space and time, but also minimize labor and downtime costs. For this purpose, in case of buried and under water pipelines, operation and maintenance management almost completely relies on automated monitoring.

3.1 Modern technical tools for the inspection and monitoring of natural gas pipelines' state

Apart from the economical interest of pipeline operators, safety and environmental aspects are of major importance for these systems due to the major consequences of their potential failure.

Therefore, a permanent control of the structural integrity of natural gas pipelines is essential what lead to the development of respective national and international guidelines and regulations, the pipeline industry is bound to [6].

As pipelines are to their largest extent buried underground or located on the sea bed, the accessibility for visual inspections is very limited. Traditional methods of pipeline inspection include *hydrostatic testing* and *direct assessment* [7]. For a hydrostatic test, a section of a pipeline is filled with pressurized water, such that its pressure exceeds its operation one. Hydrostatic testing is able to detect flaws larger than a critical size. This procedure requires an interruption of operation and is expensive. It requires the acquisition, treatment and disposal of the water.

Direct (i.e., field) assessment, is based on a detailed investigation of critical locations along the pipeline, that are deemed most likely to suffer from corrosion. For these investigations several available techniques can be applied. In case of buried pipelines this can also require digging. Based on models and observations made locally, further measures are prioritized for additional inspection, rehabilitation or replacement [7], [49].

The afore mentioned methodologies require high technical expertise, considerable effort, are costly and may require the interruption of the gas flow. Consequently, three major sensing technologies have been introduced in the last decades to control the structural integrity of pipelines over long distances

[10]:

- In-line inspection techniques,
- Fiber optic sensing and
- Remote sensing.

Apart from these three groups of sensing technologies, several other inspection techniques for local inspections of pipelines are available. The length of observation along a pipe is in these cases usually too short for the monitoring of long distance pipelines. However, for smaller sections as, for example, within compression stations or in other industrial facilities these methods can be often applied very successfully. Therefore, some of these techniques are also mentioned here.

Each of the three groups of sensing technologies were developed with specific objectives. In-line inspection tools use different measurement instruments that serve, for instance, the identification of irregularities of pipe geometry, measurement of corrosion proxies such as wall thickness and the detection of cracks and leaks. With fibre optic sensors, strains and temperatures can be measured to detect leakage and to identify pipe deformations.

Remote sensing monitoring systems on the other hand, refers to different techniques that are based on optical methods and use data recorded by systems that are usually carried by moving ground or air vehicles. In the context of pipeline damage detection these techniques are applied, for example, to detect leakage, to prevent excavation damage by third-parties or to identify external sources that could jeopardize the safety of the pipe such as uncontrolled vegetation. The description of the different optical methods is beyond the scope of this article, however, a discussion of several optical methods is made in [71] and references therein. Technologies that allow the identification of changes of the ground surface above a pipeline, indicating planting of new trees, construction or other activities, by means of optical recordings with camera systems installed on air vehicles are presented in [30].

As already noted, all the above technologies have their strengths and limitations, hence, their appropriateness for a specific case depends on the pipeline characteristics and the requirements of the operator.

3.2 In-line inspection techniques

Probably the most widely adopted approach in structural health monitoring of buried natural gas pipelines today is the so-called in-line inspection (ILI). Essentially, autonomous devices known as *smart* or *intelligent pigs* (the term *pig* derives from Pipeline Inspection Gauge) and carrying sensors, data recorders and transmitters are inserted inside the pipeline and driven by content flow, "in-line" with it. As they travel long distances in the interior of the pipe, the mounted sensors obtain continuous measurements of various parameters, depending on the desired inspection tasks; these are typically related to geometry checks, strain analysis, metal loss and crack detection. In this manner, large pipeline segments can be examined at high speeds without blocking the transportation process of natural gas. An overview about the application of ILI technologies is, for example given in [34], while a more comprehensive state of the art of commercially available ILI technology can be found in [13] and [10].

In order to assess the state of a pipeline health repetitive and regular inspections need to be carried out. In this light, the combination of inspection data with numerical models provides the basis for decisions with respect to necessary maintenance and rehabilitation measures.

Modern intelligent pigs can carry devices based on various sensing technologies [34], [10], [13]. The mainly used measurement principles are listed below [13]:

3.2.1 Magnetic flux leakage (MFL)

This very well established technology is based on the magnetic saturation of the ferromagnetic pipe wall. Powerful permanent magnets installed on the ILI tool create magnetic fields in the pipe wall so that a magnetic circle is created between the magnetic yoke system installed on the ILI tool and the pipe. The profile of the magnetic field in a flawless pipe wall is expected to be smooth and linear. Internal and external metal loss disturbs the magnetic flux density, which is a function of the pipe wall's cross-sectional area such that the magnetic field leaks out of the pipe surface.

Depending on whether the magnetic sensors are mounted on the ILI tool circumferencially or in direction of the longitudinal axis of the pipe, they can detect flaws with an orientation along the pipe axis or in circumferential direction, respectively. By MFL inspection, any kind of metal loss in a pipe wall, caused by internal or external corrosion, erosion or any mechanical action, can be identified.

A more comprehensive discussion on the technical details of MFL is made in [14]. In [53] the performance of ILI with MFL technology is verified by means of field measurements.Various parameters determining the quality of the results of an MFL inspection were identified and addressed.

3.2.2 Eddy Current (EC)

Unlike MFL technology, the EC testing method is not based on changes of a magnetic field with constant intensity but uses alternating electrical currents. In a driving coil an alternating primary magnetic field is produced. By means of mutual inductance, a flow of ECs in the surface of the neighbouring pipe wall is caused. Accordingly, a secondary magnetic field is generated in the pipe wall.

Anomalies such as flaws caused by corrosion create a change of the EC's flow direction which affects the mutual inductance. A resulting change of amplitude and phase between input and output is registered by means (of a second, receiving coil. This principle provides a highly sensitive tool to identify metal loss [13]. Uncertainties in the identification can be further reduced by combined application with MFL inspection [13] with reference to [73].

3.2.3 ElectroMagnetic Acoustic Transducers (EMAT)

Electromagnetic Acoustic Transducers (EMAT) are especially suitable for detecting stress corrosion cracking in the pipe wall and to identify disbondment or defect of protective coating. The measurement principle is based on the propagation of guided waves through the pipe wall. An impulse is generated by an arrangement of a coil in an electromagnetic field that forms an electroacoustic transducer. The energy travels then as mechanical (acoustic) wave through the pipe wall to a receiver which is located at relatively short distance. In case of a crack between emitter and receiver, part of the energy will be reflected and returned to the receiver that can also work as a receiver.

As coating is attenuating the acoustic wave, defects in the coating can be identified by analyzing the amplitudes of the received waves. Analysis of frequency, time-of-flight and wave modes allow for the distinction between cracks and other faults as well as for quantification of the crack size [13].

3.2.4 Ultrasonic testing (UT)

Ultrasonic inspection units can be used to measure the pipe wall thickness and to detect cracks in the pipe wall [13].

The measurement principles are based on the measurement of the time-of-flight of waves at very high frequencies. An ultrasound impulse is sent out by a transducer that works both as emitter and receiver. The sound wave is reflected first at the inner and subsequently at the outer wall surface. By determining the times when the two reflections arrive at the transducer and using knowledge about the sound velocity in the material of the pipe, the wall thickness is computed and any metal loss can be inferred.

For the detection of cracks in the pipe, the transducers need to be mounted to the ILI tool such that the emitted waves meet the inner surface of the pipe wall at an angle of 45°. If the sound wave reaches a crack on the pipe wall, part of the energy is reflected. Information about location, size and orientation of cracks can be therefore derived from the received signals containing the surface entry reflection as well as external and internal crack echoes. Depending on the direction in which the transducers are mounted on the carrier, cracks with longitudinal or circumferential orientation can be identified.

The transducers for UT inspection may be piezo-electric or electro-magnetic, with the latter being the case for natural gas pipelines as the former require a liquid medium to function.

3.3 Distributed fiber optic sensing

Fiber optic sensors consist one of the most recent technological development that has been successfully used to monitor civil infrastructure. According to [10], first applications were reported in the 1970s. In most cases, the measured quantities are strain or temperature. However, today, fiber optic sensors are also integrated in transducers that measure acceleration, pressure or forces [26].

One of the most widely used fiber optic sensors are fiber bragg gratings. Similar to electrical strain gauges, they allow for local strain measurements only at those positions along a fibre where Bragg gratings are integrated into the fibre. The number of bragg gratings that can be used in a single fibre is limited to about 15 to 25. This limits the applicability of this sensing technique and makes it inappropriate for the global monitoring of a pipeline over long distances.

Distributed fiber optic sensing is a more suitable technology. The sensors basically consist of a single optical fiber cable that extend over a measurement range of up to 25 km [32] or more [4].

In pipeline monitoring, there are different ways to install distributed fiber optic sensors depending on the specific measurement task. For distributed strain measurements, the fibers need to be directly attached to the pipe wall. Several options, to implement this in practice are described in [4]. For the detection of leakage in buried pipelines, it is also possible to lay the fiber cables into the backfill at a short distance to the pipe surface. When leakage occurs, this will lead to a temperature change in the surrounding material of the pipe which can be in turn identified by distributed temperature measurements.

Distributed fiber optical sensing technology relies on one of the following three optical effects: Rayleigh scattering [61], Raman scattering [36] and Brillouin scattering [37]. Technical details about these fall out of the scope of this study and may be found in relevant references. However, some general remarks with respect to the application of these measurement principles to the monitoring of natural gas pipelines are given in the following paragraphs.

3.3.1 Rayleigh scattering-based sensing

There are two different types of Rayleigh scattering-based sensor technologies distinguished: distributed acoustic sensing and distributed disturbance sensors [4].

Rayleigh scattering based distributed acoustic sensing is sensitive to the fiber propagation conditions following external vibrations such as strong impulses. Therefore, Rayleigh scattering based distributed acoustic sensing can be used, for example, to monitor damage caused by third-parties. Maximal measuring ranges are reported to be between 40 and 50 km [4]. However, the spatial resolution depends on the measuring range. One advantage of Rayleigh scattering based-distributed acoustic sensing is the high sampling rate of tens of kHz [4].

For Rayleigh scattering based distributed disturbance sensors the best performance is limited to measurement ranges of some tens of metres according [59] with a very good spacial resolution, however. Accordingly, these measurement principles are not very well suited for the application to long pipelines.

3.3.2 Raman scattering-based sensing

Raman scattering occurs due to the change of magnitude of the molecular vibrations of the fiber material [24], [25]. As these vibrations are strongly influenced by temperature, Raman scattering distributed sensing can be applied to measure environmental temperature. Accordingly, Raman scattering-based monitoring is an appropriate technology for the detection of leakage [15], [4].

3.3.3 Brillouin scattering-based sensing

Brillouin scattering-based implementations have the advantage that they are capable of long-range monitoring [27], [63]. Typical measuring ranges lie between 30 to 100 km [4], [15]. Different measuring principles exist based on Brillouin scattering which are sensitive to changes of both temperature and strain.

Several experimental studies have been conducted that demonstrate the effectiveness of the method. For instance, the results of the field application of a previously developed Brillouin distributed strain, temperature and combined strain-temperature sensing instrument are presented in [32] and [78].

Combining Brillouin scattering-based measurements with Raman scattering-based sensing which is only sensitive to temperature allows for a distinction between effects due to strains and temperatures, respectively, without the need of installing a second fibre that is not connected to the specimen such that it is only measuring temperature [4].

In an earlier laboratory test, it was taken advantage of the unique capability of distributed Brillouin sensors to measure both tension and compression at the same time, in order to detect the starting point of buckling in a steel pipe under axial compressive load [39] referring to [65], [66] and [85].

Extensive efforts in developing an integrated damage monitoring method of buried concrete segmented pipelines due to seismic effects, using distributed Brillouin scattering-based fiber optic sensors has been described in [27]. In validating the method with large-scale testing, permanent ground deformation was simulated to act on a 13 m-long pipeline assembled inside a test basin and covered with soil.

For distributed fiber optic sensing systems, typical strain resolutions of 20 $\mu\varepsilon$ at a varying spacial resolution are reported in literature [39], [15], [4]. The values given for temperature resolution vary between 0.01 and 1 K, depending on the methods used.

Further applications of distributed fiber optic sensing to the monitoring of pipelines are described, for instance, in [15], [24] and [39]. One critical issue with respect to the practical application of fiber optic sensor systems to pipeline monitoring is related to installation. Even though different methods such as integrating the optical fibers into special tapes and tubes [32] or textiles [39] have been already developed, the installation of the sensors during construction with heavy machinery and under harsh environmental conditions remains a challenge. Several proposals to solve these problems as well as further details referring to technical aspects with respect to different types of optical fibers and their application are given in [4]. There are also proposals to place distributed fiber optic sensors into the soil underneath or above a buried pipe such that temperature changes caused by leaking gas or fluid can be detected.

3.4 Local sensing techniques

While the inspection and monitoring techniques described in the two previous sections are most suitable for the application to transmission pipes, there are also other parts of a pipeline system such as compressor stations where the requirements FOR monitoring and inspection are different. In these cases, the length of the pipes are shorter, diameters are varying along the length, the pipes are partially accessible while in other instances they are buried in others.

Given the above distinct features of pipeline systems within the compressor stations but also the similarities between these stations and other industrial facilities, techniques that were developed for chemical and other plants are also applicable there. In the following, several of these techniques are briefly described.

3.4.1 Guided wave monitoring

One methodology that has been developed for the detection of cracks or corrosion pits uses ultrasonic guided waves. For the inspection of a pipe, ultrasonic waves are generated at one location and are transmitted along the pipe to both sides of the source along the longitudinal and circumferential direction. Anomalies in the pipe reflect these transmitted waves and send back signals from which information about the distance from the excitation point and attenuation can be extracted. An overview about and an introduction into this technology and its application to the inspection of pipelines are given, for example, in [43], [33] and [67].

Guided wave monitoring has been suggested especially for cases in which a pipe cannot be directly accessed for visual inspections as it is the case for insulated, buried or underwater pipes. Respective studies have been published, for instance, regarding very hot [82], underwater [52] and buried [81] pipes. From a single excitation point, typically ranges of up to 50 m in each direction (100 m in total) can be investigated depending on conditions influencing the attenuation such as degree of corrosion, coating and surrounding material [43].

One critical aspect related to the above methods is that inspections with guided waves require a respective qualification of the operator as there are many factors influencing the quality of the results such as the choice of the respective modes [43], [52]. Therefore, research is concentrated on the development of methodologies that improve the identification process by applying sophisticated algorithms such as singular value decomposition or component analysis [44], [20], [41].

3.4.2 Acoustic methods

Acoustic monitoring techniques are commonly applied to pipelines for leak detection. They typically use specific sensors to detect continuous acoustic emissions generated by a leak source and propagated through the pipe as acoustic waves. The idea of using microphones placed on the pipe wall along a pipelie for the detection of leakage was patented in 1992 [16]. Nowadays piezoelectric sensors [62], MEMS or fiber optical sensors can also be used for the identification of acoustic emission [58].

A successful laboratory study on a branched system of PVC pipes has been presented in [58]. In another experimental study, acoustic emission sensing was applied to detect cracking of concrete in a segmented model pipeline [62].

However, the application of acoustic emission to the detection of leaks in pipelines is limited by the requirement of numerous sensors as the emitted acoustic waves attenuate with increasing distance from the location of the source. Further, it has to be mentioned that the leak must generate acoustic emissions at a level that allow a clear distinction from background noise [71].

3.5 Comparative assessment of alternative monitoring techniques

The discussed pipeline inspection techniques are very versatile. They were developed with different objectives with respect to defects to be detected and properties of the pipeline sections to be monitored. Accordingly, none of the presented techniques is universally applicable in industrial practice due to their specific limitations in implementation.

For example, one crucial factor that determines the suitability of in-line inspection tools is the potential of the pipeline to permit passage of a pig unit through its body, known as ’pigability’, which depends on a number of pipeline attributes, such as the size of the pipe section, the operational pressure and the flow conditions [68]. Besides, in-line inspection requires launch and receive facilities. The operation depends on some degree of human intervention, as well as efficient energy management of the wireless sensors, transmission and storage systems. More importantly, in-line inspection techniques do not provide continuous information about the pipeline’s condition and are therefore less suitable for emergency-state rapid damage detection.

Distributed fiber optic sensors on the other hand, require much more intricate installation procedures. Further, the installation on an existing buried pipe would require a complete excavation of the pipeline. Installation of fiber optic sensors, as well as any other permanent sensors needs to be performed during the construction process. This means that both the procedures of construction and sensor installation need to be coordinated very carefully. Methodologies and devices to protect the relatively fragile measurement equipment are essential.

4 Pipeline monitoring for operation support and risk management

Decisions in operation and management of pipelines rely to a great extent on data that has been measured at different locations and transferred to the control centre. However, this does not only require the recording and transfer of measured data to a control station but also processing of a large amount of data with respect to specific objectives.

The motivation to record specific quantities can be very versatile and so is the data processing techniques adopted as well as their respective objectives. While some of the measurements serve the control of the gas flow, others provide information about the state of the transmission pipe and further components of a pipeline. Two are the major objectives:

- Operation of the pipeline to ensure provision of natural gas according to the current demand of the customers and
- Risk management to guarantee a safe and cost-efficient long-term operation of the pipeline.

The first objective concerns mainly the tasks of a dispatcher controlling the operation of a pipeline while the second is more related to maintenance and strategic decisions.

4.1 Support of pipeline operation by monitoring

The natural gas transported through a pipeline is, as mentioned earlier, pressurized in compression stations. Because the consumption of gas at the end of the pipeline is varying depending on the demand of the end users, the fluctuations caused need to be adjusted by regulating the pressure in the pipeline. This implies that it is the task of a dispatcher to control the compression stations in such a way that the current linepack level of natural gas in the pipeline satisfies the request of gas by the customers at the time when the gas reaches the end of the pipeline, which inevitably, requires a high degree of expertise

An automated Gas Pipeline Operations Advisor (GPOA) has been proposed by [74] and [80] to support the dispatcher who may be less experienced or come into stress situations during excessive demand or potential crisis management. Based on pressure and flow measurements, simulations of the gas flow are performed. The results of the simulations are then used by an expert system that applies rules derived from heuristic knowledge of senior pipeline operators such that the dispatcher receives recommendations with respect to the control of compressors.

4.2 Life-cycle and risk management

Safety and reliability are the fundamental prerequisites for the operation of a pipeline. Therefore, a reliability-based life-cycle management, as for example Frangopol [23] suggested for highway bridges, would also be sensible to be applied for the case of natural gas pipelines. One component of such a life-cycle management scheme is the monitoring of the considered system. Consequently, a respective monitoring system needs to be designed such that it can optimally provide the data which is required within a reliability-based life-cycle management scheme, a topic that has been addressed, for example, in [79] where a methodology has been suggested and applied to an offshore wind turbine structure that can also be adapted to natural gas pipeline systems.

Like other infrastructure systems, also many natural gas pipelines have already approached their design life time. Owners have then to decide if they can continue operation or if their pipeline has to be abandoned. To ensure safe and reliable operation, regular inspections and continuous monitoring can be implemented, a procedure that is also accepted by respective national regulations as pointed out in [34].

One key issue in a monitoring scheme is the reliable and robust identification of damage in the considered system. Among numerous procedures that have been developed over the last decades, there is one vibration-based approach that has already been successfully applied to different industrial structures such as bridges and offshore structures [75]. This method which is based on the normalized cumulative spectral energy of vibration response measurements has also been applied to identify a fatigue crack in an industrial pipe system during laboratory tests. It is expected that this technique can also be applied to certain components in natural gas pipelines such as compression stations. For an application to buried and underwater transmission pipes, adaptations depending on the sensor technique used would be necessary.

Information about the structural integrity based on monitoring is one component of a framework that was developed to estimate certain risks linked with industrial processes as input into decision processes [2]. This framework has been implemented and applied, for instance, to estimate the risk of failure due to extreme wind and wave conditions of an offshore wind turbine structure.

Reliable information about the risk of structural failure is one of several factors that need to be taken into account if decisions with respect to maintenance, rehabilitation, strengthening or renewal of industrial facilities have to be made. In case of systems such as natural gas pipelines not only technical and financial but also environmental and societal criteria have to be included into the decision process. Risk management of natural gas pipelines is therefore a multi-objective task involving multiple criteria.

This gave reason to apply multicriteria approaches such as the elimination and choice expressing reality approach (ELECTRE) [12] and multi-attribute utility theory (MAUT) [11], [1], [40] to the risk assessment of gas pipelines. These algorithms were designed to assign alternative solutions of a problem into categories such as 'acceptable', 'unacceptable' or 'intermediate' [18]. An overview about different multicriteria and multi-objective decision making techniques are given by [17] and [46].

5 Conclusions

As natural gas pipelines consist essential lifelines of modern industrial societies, their potential damage (i.e., from deterioration to not only results into an interruption of supply but it can also have severe and sometimes irreversible consequences.

Therefore, resilience and robustness of natural gas pipelines has attracted scientific attention as a means to guarantee safety as well as disruptive and reliable operation and service. In this context, monitoring and inspection of pipelines are important elements to reliably assess their structural integrity.

This paper reviews, in a comparative sense where possible, numerous state-of-the-art and practice techniques and methods for inspection and monitoring of natural gas pipelines. Successful cases studies are also reported along with respective limitations and challenges, the latter including installation and optimal sensor placement issues. The paper concludes with future developments are also discussed in light of risk assessment procedures and life-cycle management of pipeline networks.

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