Comparative Review of Pipelines Monitoring and Leakage Detection Techniques

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***Abstract*—The oil and gas industry owns expensive and widely-spread assets. Any fault in this complex transportation network may result in accidents and/or huge losses thereby triggering various environmental and economic issues. Thus, real-time monitoring and preemptive measures based on fault propagation analysis limit some of these consequences. This paper presents a comprehensive review of the techniques used for monitoring and fault detection of oil pipelines. The pros and cons of the most common techniques are mentioned along with a review of the recently reported literature. It is anticipated that wider dissemination of the recent developments in pipelines monitoring and inspection will reform the oil sector from the perspectives of surveillance, security, inspection and emergency response.**

Keywords—Pipeline system, infrastructure monitoring, leak detection, oil sector, safety, drones

I. Introduction

The oil and gas industry consists of transmission pipelines expanded over around 3 million Km and globally the industry holds a market share of over 8680 Million USD [1]. The overall length of the pipelines is increasing at a significant rate since new pipelines are being installed between cities and even between countries. During design process of pipelines, reliability and fidelity are essentially taken into account. However, over the length of its lifetime, the probability of occurrence of a leakage in the pipeline cannot be neglected due to various factors including abrupt pressure surge, corrosion, traffic loading, soil movement etc. The leakage results in tragic incidents presenting serious consequences related with financial losses as well as environmental damage. Examples of catastrophic incidents include Exxon Valdez and Deepwater Horizon oil spills etc. [2].

The challenges to maintain high production and maximum returns highlight the importance of state-of-the-art techniques for the inspection of setups like process plants during normal operation which is majorly inaccessible due to their enormous and complex infrastructure [3]. The infrastructure for monitoring typically consists of offshore and onshore online flare systems, flare support structures, splash zones and towers and columns etc. The critical penalties due to pipeline leakage highlight the need to have precise leakage detection methods that can quickly diagnose a failure fault to undermine the consequences in terms of expensive material and environmental hazards. To achieve these objectives, degree and type of damage as well as its location need to be determined accurately to avoid any wrong and nuisance leak alarms.

Also, the continuous increase in volume of these transmissions is another stipulating reason to have a cutting-edge solution for their monitoring and inspection. Therefore, the earliest detection of any damage on or near the surface of the pipeline in order to minimize the hydrocarbon loss and decrease the effect of environmental hazard is one of the major challenges in the oil and gas industry [4]. This is also very pertinent to KSA, which is the largest oil producer and aims to increase its market share from 40% to 75% by 2030. This ambition can only be achieved by benefiting from cutting-edge technological advancements.

This paper presents a review of methods for pipelines monitoring and leakage detection. The remaining of the paper is organized as follows: Section II discusses an overview of techniques for fault detection. Literature review is reported in Section III. Finally, Section IV concludes this paper.

II. Techniques for Leak Detection

Scientific and engineering communities have presented various techniques to detect leakage in an operational oil pipeline. Some of these techniques have been adopted from failures in water pipelines or gas pipes in the form of rupture or explosion respectively. These techniques can be as simple as manual visual inspection and can be as sophisticated as a model-based algorithm. Each of the techniques carry its own pros and cons for effective detection and localization of pipeline leakage. These techniques have been grouped into different categories by various researcher. Furness *et al.* [5] categorized these into three groups: simple systems, computer-based systems and pig based monitoring systems. In another study [6], the classification relies on media used for leakage detection i.e. acoustic, hydraulic, online pig based and offline observation. [7] categorized the leakage detection techniques into hardware and software based methods. The present work classifies the techniques into three groups [8]: visual, exterior and interior based methods.

A. Visual Techniques

Modern day drones have totally transformed the concept of 'flying vehicles' in various spheres of life. They are now much more than recreational aerial crafts that could only be remotely controlled in the past. Thanks to technological advancements, drones are now self-directed and have distinctive characteristics to fly in nearly all types of weather conditions. They are particularly used in aerial imagery and video recording of places where human intervention is either cumbersome or dangerous [9].

An intelligent Unmanned Aerial Systems (UAS) centered on a drone or an Unmanned Aerial Vehicle (UAV), has the potential to offer risk-free, time-optimal and cost-effective real time monitoring solution with minimal human intervention. A drone-based inspection consists of three major steps; using off-the-shelf drones to obtain high-resolution field of view of the intended infrastructure, developing computationally-inexpensive fault analysis and propagation machine learning algorithms to extract information pertinent to the particular stage of fault occurrence and, finally, testing and validating the solution on a real site in coordination with the concerned parties.

The instant aerial data captured with the help of a drone has opened new horizons for revolution in industrial applications, specifically for oil and gas industry [10]. The gist of the technique is based on automatic processing of the raw data from aerial photography of the large scale infrastructure from various dimensions and converting it in to meaningful data which can be used for both predictive analysis and on spot decision making [11]. Figure 1 illustrates conceptual view of this approach.

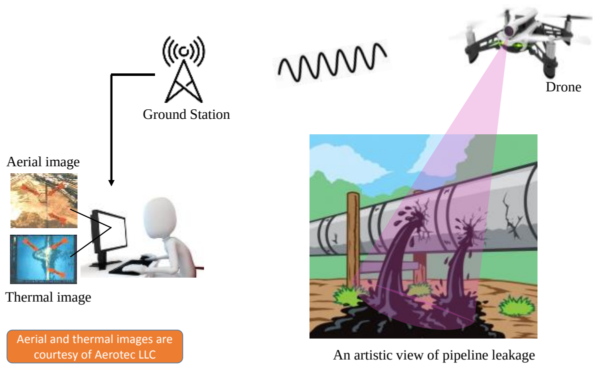

Fig. 1. Working principle of drone based technique

A UAS is a cost effective, efficient and safe solution for the fault detection, since there is no disruption in the normal operation and there is no special need of shutting down the facility for inspection. This is particularly beneficial for online flares where traditional inspection is done by shutting down the facility for visual inspection. Before the advent of drones, construction contractors used to hire helicopter for the visual inspection of major sites like Cushing Oklahoma-the oil crossroads of the world [12]. This method had two major drawbacks: first, it was expensive and secondly the visual data comprises of very limited images from specific perspectives [13]. However, with the use of drone images and videos the required images are captured and processed very effectively: an entire installation expanded at an area of 18 acres can be covered in only 15 minutes.

Generally, a UAS has three different modes which are selectable depending on the requirement and nature of the operation. The first mode is the Manual mode, in which the pilot fully controls the UAS by commanding through the joystick. In this mode of operation, a skilled pilot is required to control the UAS as no sensor information is available. The second mode is semiautomatic mode in which pilot is assisted by automatically stabilized control system. The stability of UAS is achieved based on the information of the sensors mounted on it. The pilot on the ground station can efficiently control the UAS by using the available data about this flight. The third mode of operation is called fully automatic control mode which permits the UAS to perform operations without any involvement of a pilot on the ground station. This way a UAS can take off and land on the ground without any intervention of the pilot. In both the semiautomatic and fully automatic modes stability of the UAS exclusively depends upon the control design method employed on its autopilot. The controller design of a drone is a challenging task since these systems are highly nonlinear and under-actuated Multiple Input Multiple Output (MIMO) type in nature. Trivial control strategies based on linear control laws are inadequate for drones [14]. Thus, more sophisticated modern and robust control techniques [15] e.g. Sliding Mode Control (SMC) and $H\infty$ control can be employed to reduce the environmental effects and uncertainties in the system to avoid instability and chaos [16]. Figure 2 presents a basic closed-loop feedback control system for a quadcopter-based UAV while Figure 3 illustrates over-performance of a SMC based law in comparison to Proportional Integral Derivative (PID) with Computed Torque Control (CTC).

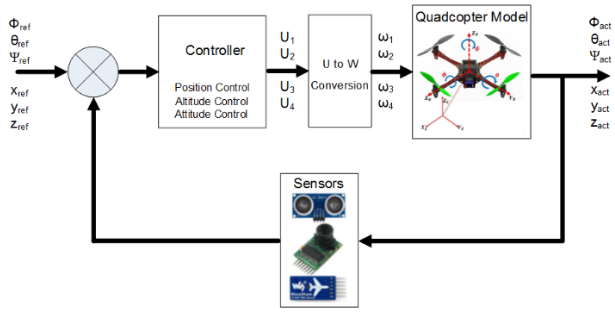

Fig. 2. A closed-loop feedback system ensures that desired parameters are effectively tracked. The desired parameters include X, Y, Z, roll (φ), pitch (θ) and yaw (ψ) angles

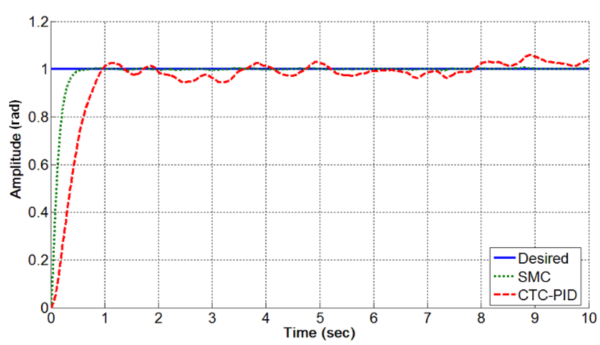

Fig. 3. Modern control techniques like SMC can handle disturbances and uncertainities while classical control laws like PID are unable to do so. Step responses of both kinds of control strategies are shown that demonstrate tracking performance in the presence of disturbance [17]

Two types of UAV platforms are used for the inspection: Fixed-wing and Rotary-wing aircrafts. Both have their own merits and demerits. The fixed wing UAVs are suitable for long endurance tasks and are very stable in extreme weather conditions because of being energy efficient [18]. The rotary-wing aircrafts, on contrary, are not very energy efficient and are less suitable for long surveillance projects, typically their flight time is limited from 20 to 60 minutes. However, such aircrafts have the outstanding maneuverability and landing and taking off convenience without any need of large open spaces, since it can hover, take-off and land vertically [19]. The phenomenon is known as Vertical Take-Off and Landing (VTOL) and this type of UAS gets the obvious advantage for deployment of sensor closest to the source and hence are preferred for field operations that have runway limitations. In both the cases the selected models' frame may require modification in order to carry the trace gas detection system to be deployed [20].

The type of the data and information obtained from the mission depends upon the type of sensors carried by the UAV Platform. The sensors have two main types: active and passive, depending upon the energy eliminated from the source object. Active sensors emit their energy themselves in the form of radiations whereas the passive sensors rely on solar energy for illumination. The selection of sensors amongst active sensor (Visible, Multispectral, SWIR, Thermal IR, Video, Stereo Cameras, Gas IR Camera) and passive sensors (Lidar, Radar, Laser Gas Detector, Laser Fluorosensor) also defines the lifting and carrying characteristics needed by the UAV Platform [21]. Further to the use of aircraft and sensors, a series of auxiliary equipment have also been employed in order to make the mission successful. The most commonly used system and elements in this domain includes position and navigation system, communication medium and autonomous flight supporting software etc.

B. *Exterior Techniques*

These techniques are based on several man-made sensing mechanisms to observe the exterior of the pipe. Consequently, specific abnormal features in the vicinity of the pipelines can be determined. These abnormalities detection also includes oil leakage. While various techniques in this category use different sensing principles, they need a physical contact between the sensor and the pipeline. Prominent examples of these techniques uses acoustics sensors, vapour sampling, capacitive sensing, electromechanical impedance, ground penetration radar etc. The first two sensing mechanisms are discussed below:

(i) Acoustic Sensing

This technique involves placing the transducers in direct contact with the wall of the pipeline at two locations encompassing the suspected location of leak. The transducers pick up intrinsic signals that escape from a punctured pipe. A typical setup of an acoustic leak correlator consists of portable computers or microprocessors which analyzes the signals received from both transducers and determines location of leak based on time delay and acoustic speed. This speed is a function of known parameters like pipe size and information about pipe's material. Figure 4 illustrates a schematic of an acoustic correlator.

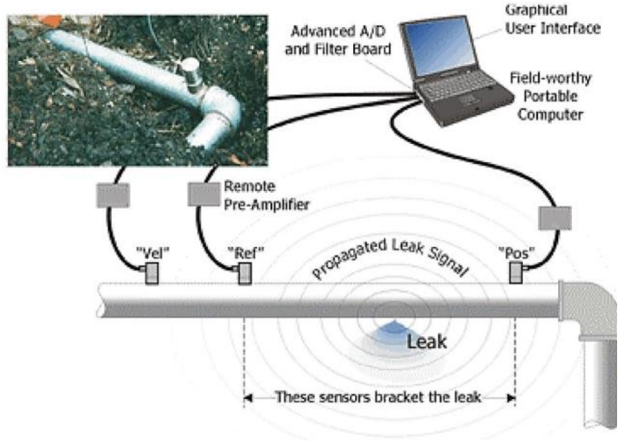

Fig. 4. An acoustic leak detection correlator (PALS System from Vista Research Inc.)

(ii) Vapour Sampling

This technique determines oil spillage based on measurement of gas concentration w.r.t. the pumping time. A typical setup (see Fig. 5) consists of a pressure dependent tube, a pump a gas detector. In case of a leakage, vapour gets diffused into the tube and thus generating a signal representing hydrocarbon flit. This technique is particularly suited for detection of small concentrations of diffused gas. However, due to the high detection time involved, this technique is not much effective for pipelines under the sea.

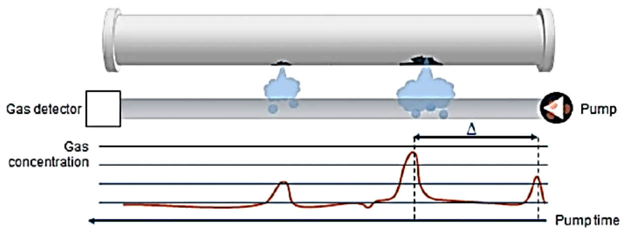

Fig. 5. Vapour sampling method for leak detection [22]

Other exterior techniques for leakage detection include Capacitive sensing, Electromechanical impedance and Ground penetration radar. Capacitive sensing method, usually used in subsea operations is based on measurement of variations in dielectric constant of the medium contiguous to the sensor. This method suffers from false alarms and also requires mitigating buoyancy effects, which carries the leak medium away from vicinity of the sensor.

On the other hand, techniques based on electromechanical impedance relies on measurement of structural variations resulting from damages in pipelines. The sensor consisting of small piezoelectric patches measures dynamic impedance. A single transducer can act as a sensor as well as an actuator. However, this method is difficult to be used in environments with high temperatures.

Finally, ground penetration radars use a moving antenna to transmit electromagnetic waves into the object to be monitored. The leak information is reliable and is very comprehensive. However, the methods is costly and needs a skill-full operator.

C. Interior/Computational Techniques

These techniques are based on computational algorithms that uses measurement of certain parameters inside the pipe. These parameters include pressure, density, temperature, flow rate, volume etc. By comparing the sensory information of internal pipeline status acquired in two different sections, leakage occurrence can be determined using several methods like negative pressure waves, volume-mass balance, digital signal processing, dynamic modelling etc.

In pressure based technique, a typical setup consists of two pairs of sensors each installed at the beginning station and the end station (see Fig. 6). The leakage can be determined based on identification and detection of negative wave front associated with the pressure wave caused by the leak event. The pros of this technique are determination of the location of leakage and low overall cost while the drawbacks include high hysteresis, sensitivity to vibrations and resistance due to moving contact.

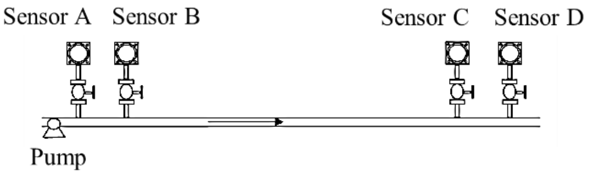

Fig. 6. Working principle of pressure based technique

In volume (or mass) balance methods, the presence or absence of leakage in a pipeline is determined by inletting volume and then measuring the outlet flow. In case of no leakage, leakage volume (V_L) as given by (1) will be zero.

$$V_L = V_{in} - V_{out} - \Delta V \tag{1}$$

where V_{in} and V_{out} are metered inlet flow and metered outlet flow respectively. ΔV is pipeline pack or inventory and can be computed based on water hammer equations. The accuracy of flow meters is critical to accurately determine the leakage volume.

Wireless Sensor Network (WSN) based method involves interconnection of integrated network using leak detection sensors. The collected data at a node is then sent to the control center for processing. Figure 7 illustrates working principle of WSN based technique. This technique can collect and transmit data for long distance and offers continuous, permanent and efficient control. The drawbacks include security and battery issues and distraction.

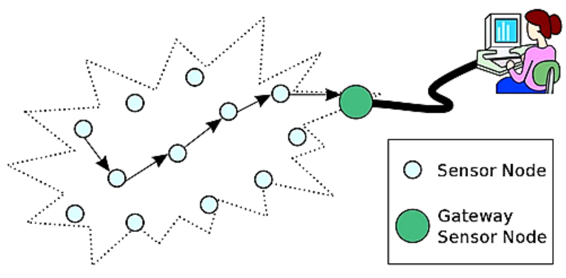

Fig. 7. Working principle of WSN based method

Digital Signal Processing based methods for leakage detection relies on information extraction, which can be in the form of amplitudes or wavelet coefficients. A typical sequence of steps include [8]: Data acquisition, Signal pre-processing, Feature extraction, Pattern classification and finally leak detection is accomplished by comparing the pattern with the threshold. Other software based techniques include frequency response diagram, transience behavior of fluids, grey relational analysis, genetic algorithm combination with inverse transient and harmonic wavelet.

Recently, many researchers are exploring dynamic models to detect anomalies in both subsea and surface pipelines. Dynamic modelling-based methods involve formulation of analytical models that describe operational behavior of a pipeline using physics laws. Both statistical as well as transient points of views are considered in this method.

III. Literature Review

Various techniques for leakage detection have been further explored for their pros and cons. These benefits and drawbacks are related with performance, operational constraints, economical and other aspects. Also, notable reported research works on each of the mentioned techniques have been investigated. Table I presents summary of leakage detection techniques.

IV. Conclusion

This paper presents a brief review of techniques and methods for monitoring and leakage detection in oil and gas pipelines. Rigorous analysis and discussion of these methods is vital in smooth functioning of a plat or an industry especially in a safety critical environment. A recent trend to deploy drones for inspection and monitoring of oil and gas setups is also highlighted. The merits and demerits of various leakage detection techniques are also presented.

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TABLE I. Summarized literature review of techniques for pipeline leakage detection

Category	Technique	Ref.	Remarks
Visual	UAV/Drone	[23]	**Pros:** Quality imaging and live streaming, affordable cost-saving technology, ease in control **Cons:** Privacy violation, endangering public safety, potential threat to nature, unclear legislation
Exterior	Acoustic	[24]	**Pros:** Economical, portable, easy installation **Cons:** Noise sensitivity, high false alarm rate
	Fibre optics sensing	[25]	**Pros:** Low noise sensitivity **Cons:** High cost, lack of durability
	Ground penetration radar	[26]	**Pros:** Reliable, Timely detection of leakage **Cons:** Signal distortion in clay soil scenario, Requirement of highly skilled operator
	Capacitive sensing	[27]	**Pros:** Works in non-metallic targets **Cons:** Direct contact with the leaking medium is required
	Fluorescence	[28]	**Pros:** Easy and quick scanning, high spatial coverage **Cons:** Medium should exhibit natural fluorescence
Interior	Volume-mass balance	[29]	**Pros:** Noise insensitive, portable, low cost **Cons:** Cannot localize leak
	Negative pressure wave	[30]	**Pros:** Can localize leak, Fast response **Cons:** Adequate only for large instantaneous leaks
	Wireless sensor network	[31]	**Pros:** Collect and transmit data over long distance, continuous and permanent control, efficiency in control **Cons:** Security, battery issues, distraction
	Digital signal processing	[32]	**Pros:** Optimal performance, Can detect and localize leaks, Simple and flexible implementation **Cons:** High probability of false alarms, Noise maskable
	Dynamic modelling	[33]	**Pros:** Robust and can handle large amount of data **Cons:** Complex, computationally expensive