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Leakage phenomena control methods to ensure high integrity and safety standards in pipeline systems

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1. Introduction

The use of pipelines, or systems relying on the same principle, has always been the most energy-efficient way to transport large quantities of liquid. The first were the famous Roman aqueducts; several centuries later water pipelines followed by oil pipelines made their appearance. Later, when gas resources started to be exploited, also gas pipelines started to spread out with the purpose of transporting fluid from the production field to refinery or power plants, covering ever greater distances.

One of the main problems affecting the management as well as reliability and safety of pipelines is constituted by leakages: fluid loss from small or even large ruptures on pipe wall, loss from poorly sealed fittings, valves or other pipeline's devices, loss caused from thefts, even till catastrophic ruptures.

Consequences change a lot according to the type of fluid transported, particularly according to its hazardousness.
In case the leaking fluid is water, since it is not an hazardous liquid, in general it does not have any damaging consequence neither on the environment or living being nor about safety point of view. On long term it can lead to damages on infrastructures such as roadways, particularly to foundations erosion, or it can slightly damaging buildings. However it can have negative consequences for the pipeline operator and for consumers mainly in terms of interruption or irregularity of the service provided as well as, for the operator only, in terms of volume of product loss so financial damage.

Concerning oil and gas transport it's a different situation: we are talking about hazardous fluids which are highly flammable, explosive, toxic for animals and polluting to the environment.
Even a small leakage from an hydrocarbon pipeline can lead to critical consequences: in case the fluid leaks out and the product get ignited catastrophic events such as jet fire, explosion, pool fire and consequently toxic smoke release can occur with a high risk of human injuries or death, whether to pipeline personnel or civilian living nearby.

The release of these products into the environment involves a damage in any case and in case of catastrophic rupture of the pipeline it can cause an environmental emergency. When released into the environment they can disperse into rivers or into the sea affecting animal species health, or it can penetrate into the soil polluting it. Also oil penetrating into the soil can reach water reservoirs and contaminate them.
In addition to the obvious economic loss due to the waste of product, repair costs and eventual costs due to system shut down, pipeline operators undergo to severe penalties for the environmental damage caused.

Results achieved by a study conducted by the US *Department of Transportation's Research and Special Programs, Office of Pipeline Safety* (RSPA/OPS) about hydrocarbon pipelines accidents and their causes for the two-years period 2002-2003 can be useful to have an idea about the magnitude of financial damage caused by leakages.
As we can observe on Table 1. leakage-like accidents concerning liquid pipelines only led to 175,475 barrels of product lost and a property damage of 74.8 million of dollars approximately, while leakages on gas pipelines led to a damage of 66.35 million of dollars. In addition in that period 3 death and 18 injury cases occurred.

Exactly because of what said above pipeline operator companies as well as the specific industrial sector always gave great importance to leakage problem developing methods, technologies and practices to prevent, monitor and detect leakages, in addition to repair them.
In recent times the increase of gas exploitation and the subsequent significant development of even longer pipelines, therefore followed by frequent leakage occurrence, brought back the attention on pipeline leakages and on new effective solutions. Also, the same necessity came from water transport field which nowadays is going towards ever more efficient and sustainable management strategies and use.
Particularly it became necessary to have *real-time* monitor systems capable to detect, even small, leakages with a short delay time and warning it, in addition to provide an accurate localization of the leak and an estimate of its size. It is required these systems to be sensible to small leakage, reliable and with a low false-alarm rate.

This study aims to understand the problem of pipeline leakage first starting from knowing causes and initiating events, then strategies, techniques and best practices implemented to prevent them to occur.
We wanted to understand systems employed to monitor pipeline health and integrity as well as the proceeding of eventual flaws which already identified in previous monitoring campains.
We made an overview study on the different detection methods and strategies which are widely used and consolidated but focusing on the most recent and performing methods which more meets new market requirements.

2. Flaws, damages and failure mechanisms as source of possible leakage

Accidents, failure events and damages occurring every year to transport pipeline and related equipment are a subject of great interest. The effects of these events have impacts whether on continuity of service delivery to the costumer, on safety related aspects, on environmental safeguard issues, and more in general on economics aspects. At this point it becomes extremely important to examine and quantify the different causes leading to the over mentioned events so to be able to concentrate efforts and investments towards the most convenient and effective solutions.

Considering that the totality of accidents, failures and damages we are talking about comprehend or generate at least transported fluid losses, we believe it is fundamental an overview with the purpose of identifying the initiating events and phenomena which lead to failures and so leakages occurrence.

Important consideration can be done by observing data extrapolated from the two-year report (2002-2003 period) about pipeline accidents and their causes, compiled by the U.S. Department of Transportation's Research and Special Programs Administration, Office of Pipeline Safety (RSPA/OPS), which are summarize in the following Table 1.

We can observe how in case of Liquid transport, between the different causes of incident, top positions in terms of *number of incidents* occurred are occupied by *Corrosion* followed by *Material-Welding failure* and *Excavation* (respectively 25.4%, 16.5%, 14.7%); this first place is confirmed also in case of Gas pipelines where the same causes occurs with a percentage of 25.6%, 20.0% and 17.8% respect to the total number of accidents.

Hazardous Liquid Pipeline Accident Summary by Cause 1/1/2002–12/31/2003

Reported Cause	Number of Accidents	% of Total Accidents	Barrels Lost	Property Damages	% of Total Damages	Fatalities	Injuries
Excavation	40	14.7	35,075	$8,987,722	12.0	0	0
Natural forces	13	4.8	5,045	$2,646,447	3.5	0	0
Other outside force	12	4.4	3,068	$2,062,535	2.8	0	0
Materials or weld failure	45	16.5	42,606	$30,681,741	41.0	0	0
Equipment failure	42	15.4	5,717	$2,761,068	3.7	0	0
Corrosion	69	25.4	55,610	$17,775,629	23.8	0	0
Operations	14	5.1	8,332	$817,208	1.1	0	4
Other	37	13.6	20,022	$9,059,811	12.1	1	1
Total	272		175,475	$74,792,161		1	5

Natural Gas Transmission Pipeline Incident Summary by Cause 1/1/2002–12/31/2003

Reported Cause	Number of Incidents	% of Total Incidents	Property Damages	% of Total Damages	Fatalities	Injuries
Excavation damage	32	17.8	$4,583,379	6.9	2	3
Natural force damage	12	6.7	$8,278,011	12.5	0	0
Other outside force damage	16	8.9	$4,688,717	7.1	0	3
Corrosion	46	25.6	$24,273,051	36.6	0	0
Equipment	12	6.7	$5,337,364	8.0	0	5
Materials	36	20.0	$12,130,558	18.3	0	0
Operation	6	3.3	$2,286,455	3.4	0	2
Other	20	11.1	$4,773,647	7.2	0	0
Total	180		$66,351,182		2	13

Table 1. Oil & Gas pipeline accident summary by cause 2002-2003, RSPA/OPS

Another datum which address us in understanding how the different causes influence pipeline management and preventive actions planning is the *damage* caused by each different cause category which includes product loss, system shut down cost, repair costs and environmental related costs.
Damage percentage values we see for the over mentioned causes are 23.8%, 41.0% and 12.0% in case of liquid pipelines and 36.6%, 18.3% and just 6.9% in case of gas pipelines.
Despite these *damage* data are quite significant they cannot be thought as absolute, but of course they suggest us which are the “weak points” of pipeline system.

This last assertion derives from concepts concerning *Reliability Theory* field: if we link the percentage of incidental events occurred for a singular cause category to the *frequency* f of occurrence, and we consider the percentage value over total damage as the *damage* D, a greater improvement of the Reliability of the pipeline system will be obtained by intervening to reduce frequency than intervening to reduce the damage. This reasoning still remain too approximate; further and deeper studies are required to answer these questions but we are talking about a different study field which is not part of this analysis.

What we are able to say instead is that a distinction can be made between initiating events, damages and flaws depending if the causes of their occurrence have to be researched in the so called *pre-service* phase or during *in-service* phase. This distinction can be helpful to understand where and when it is necessary to act with specific and careful preventive actions.

2.1. *Pre-service phase*

2.1.1. LAMINATION DEFECT

Plate lamination defect represents one of the primary processing discontinuity which originates during hot or cold forming steel (or alloy) processes. It has the aspect of a flat and thin subsurface separation existing inside metal plate, parallel to the surface of the plate itself.

This defect can rise during pipe manufacturing processes: in case of carbon steel a plate is produced by hot or cold rolling a thick slab. The plate is then bent by multiple consecutive processing through a bending machine until a cylindrical shape is obtained and, after welding the two edges along the longitudinal axis a pipe has so been realized.
However, returning to plate manufacturing, the thick slab passes through machine's rollers many times until the desired thickness is achieved. Each pass lead to an increase in the area of the plate and a reduction in thickness. This causes every discontinuity originally present in the metal slab, such as porosity or inclusion, to become elongated in the direction of rolling so to result in laminate formations within the metal plate.
The mentioned inclusions consist in micro-particles of sulfides, oxides, nitrides, silicates, etc. among which the first two are those who can generate migration phenomena, and subsequent porosity in the center of the plate as it starts cooling from outside inward.
Initially inclusions remain in the center for the duration of the subsequent hot or cold processing but, in case in case enough inclusions accumulated within the plate, or the metal sheet need to be thinned furthermore, inclusions get exposed and give birth to separation of two distinct layers of metals at the end of the rolling processing which is what we call *laminations*.
Laminations affects steel plates, and so pipes, critically reducing their strength in the thickness directions and are highly undesirable for dynamic loaded structures like high pressured vessels and pipes.

2.1.2. WELD POROSITY

Weld porosity is nothing else than gas pores found in the solidified bead, both in the center or in the surface of the weld. The reasons of porosity occurrence can be grouped in four categories (one of which is made by further sub-causes) as we list here below:

1. WELDING ATMPOSPHERE CONTAMINATION
   - Poor shielding gas flow
   - Excessive shielding gas flow (it can make some air to be aspired by the gas stream)
   - Excessive wind speed affecting the welding area (gas shield may be blown away leading to a poor shield gas flow)
   - A critically plugged gas nozzle or more in general a damaged gas supply system

2. EXCESSIVELY OXIDIZED WORK PIECE SURFACES
3. INADEQUATE DEOXIDIZING ALLOYS IN THE WIRE
4. PRESENCE OF EXTRANNEOUS MATTER ON THE SURFACE TO BE WELD

2.1.3. WELD UNDERCUTTING DUE TO INADEQUATE PENETRATION AND FUSION

This type of flaw takes on the appearance of a groove in the parent pipe material along the edges of the weld and its usually found in lap fillet welds but also in fillet and butt welds which fits more with our topic.
The cause of these defects have to be attributed to inadequate welding execution parameter, particularly travel speed and arc voltage.
The effect of an excessive speed causes a too rapid solidification of the weld bead which will have a peaked shape, then surface tension forces do their part drawing the molten metal along the edges of the bead a pile it up. The same problem affects melted portion of the base plate.

At this point what does happen is that the undercut groove appears exactly where melted base material has been drawn into the weld and cannot wet back adequately because of solidification rapidity.

As we mentioned above also an excessive arc voltage can give rise to weld undercutting, particularly in case spray arc weld is employed. In general it is suggested to keep short the arc length not only to reduce the probability of having undercutting but also to increase penetration and weld soundness. In addition it must be said that also an excessive welding current leads to undercutting formation.

2.1.4. HOT CRACKING

These cracks originates during welding operation, when materials involved go beyond $700°C$. They occur because of the presence of impurities, particularly Sulfur and Phosphorus, in the welding material as a consequence of the use of poorly clean electrodes. During welding procedure S and P particles accumulate at the edges of metal grains and concentrate mainly in the core of the metal body where solidification last occurs. Since fusion points of S and P are considerably lower than metal one, when this last is going to become solid S and P are not resulting in shrinkage strains which induce cracks.
This type of cracks affect the central part of the welding and occurs almost immediately, sometimes even while the welding is still going on.

2.1.5. HYDROGEN INDUCED CRACKING

Hydrogen induced cracking (HIC) is a common type of failure occurring in the weld metal or in the heat-affected zone (HAZ) due to hydrogen presence involuntarily resulting from welding procedures. It is also known as hydrogen assisted cracking (HAC) or *cold cracking* because, despite it is triggered by mechanisms actuated during welding processes, it starts to occur only when the weld has cooled down to room temperature.
Hydrogen atoms introduced into the weld during welding process comes from three sources which are:

- Moisture deposited on electrode, flux, shielding gas or environment
- Contaminants containing hydrogen such as grease, oil, water, cutting fluids on the surface of the metal to be welded
- Decomposition of cellulose-based electrode coatings and combustion products of oxyfuel welding

After the welding has been completed the metal still maintains elevated temperatures which increases hydrogen atoms solubility, allowing them to disperse into the weld and the HAZ.
During their dispersion hydrogen atoms combine together forming H_2molecules when they find enough space inside very small metal voids. This produces pressure within these voids and a buildup in the metal, causing it to loose tensile strength and ductility which can end in a delayed cracking which can occur even 72 hours after the welding when the material cools down to ambient temperature.

About their appearance it must be said that HIC cracks forms and stacks vertically, which means crack path develops perpendicularly respect to the plate or pipe wall surface causing the crack to be shot and packed with the others.

2.1.6. STRESS-ORIENTED HYDROGEN INDUCED CRACKING

Despite its name is similar to HIC they rely on two working mechanisms which are different. This flaw occurs in HAZ of welds, particularly in thick and restrained welds, because of the presence of residual stresses which worsen the effect of hydrogen atoms inclusions.

Given the presence of HICs and when these short cracks are quite stacked, the "necessity" of the metal to release residual tensions gained with welding forces HICs to link up. With a quite rapid sequence a through-the-wall crack generates by shearing the ligaments between the packed HICs . Such a stepwise cracking mechanism, also called cross-tearing, is most common in pipelines then in vessels or tanks despite these lasts are characterized by lower yield strength; conversely to what can be thought SOHIC mechanism is not much dependent on material strength but mainly on loading and service conditions.

2.1.7. LAMELLAR TEARING

“Lamellar tearing is a cracking phenomenon which occurs beneath welds, and is principally found in rolled steel plate fabrications. The tearing always lies within the parent plate, often outside the transformed (visible) heat-affected zone (HAZ), and is generally parallel to the weld fusion boundary.

For tearing occur, three conditions must be satisfied:

1. Strains must develop in the short transverse direction of the plate. These strains arise from the metal shrinkage in the joint but can be greatly increased by strains developed from reaction with other joints in restrained structures.
2. The weld orientation must be such that strains act through the joint across the plate thickness, i.e. the fusion boundary is roughly parallel to the plate surface.
3. The material must be susceptible to tearing, i.e. in the joint shown the horizontal plate must have poor ductility in the short transverse (through-thickness) direction.

2.1.8. MECHANICAL DAMAGE DURING EXCAVATION

During the various phases preceding pipeline construction, such as pipe joints transport, loading/unloading, storage, and during the construction phase itself, pipeline components ,especially joints, are subjected to the risk of mechanical damage. Precisely the most critical factors for a joint are its handling by cranes and movements of dozers and vehicles passing nearby.
The most common flaws and damages a joint can be affected by are *dents* and *gouges*.

GAUGE
We talk about gauge when a whatever object mechanically remove (or relocate) a portion of material from the surface of a component, generating a local reduction of the material thickness or a local thinning of pipe wall in our case. Geometrically a gouge is characterized by a length greater then width, resulting so with an elongated shape. Another feature is that the material removal occurred by a cold working as it can happen when a vehicle distractedly rubs against a stored joints passing nearby.

DENTS
Like gouges also dents can be generated by a similar sequence of events or, like frequently happens, when cranes lifts joints these can swing in the air striking an object. The main difference is that for dents, material removal or scratching on the pipe surface does not occur; what does occur is a deformation of the pipe wall, generally inward.

2.2. *In-service phase*

2.2.1. UNIFORM ATTACK CORROSION

It is the most common form of corrosion. It consists in a zone of the metal surface where the exposition to an aggressive environment, or fluid in case we are talking about internal corrosion, triggered electrochemical processes generating corrosion/oxidization products in a quite extended and uniform manner. Additionally the proceeding rate of metal deterioration is approximately the same in every direction leads to a fairly uniform thinning of the pipe wall or material in general.

2.2.2. LOCALIZED CORROSION

The general definition of localized corrosion talks about a corrosion phenomenon which targets a specific area of the metal structure. Three different type of localized corrosion exists as follow:

PITTING
It consists of a narrow and deep hole forming in the metal surface which once triggered proceeds with a high penetration rate. Usually it forms as a consequence of de-passivation of a small area: this area, which is kind of isolated from the rest of the metal, acquires anodic properties while the remaining part of the metal acquires cathodic behavior giving rise to a local galvanic reaction. The unbalanced reacting surface proportion are the cause of the rapid deterioration rate which can lead the metal to an unexpected failure. Another feature characterizing pits is that they are often difficult to be detected because of their small size and because of corrosion products which can cover and hide them.

CREVICE CORROSION
Crevices have a somewhat similar appearance to pits. They form when a stagnant micro environment establish in a narrow space such as under gaskets, washers or clamps. The corrosion process triggered because of depletion of oxygen or acidic conditions into the narrow space.

FILIFORM CORROSION
It is a form of oxygen cell based corrosion which occurs on metal surfaces underneath paint or coating layers in case some water breaches them. It usually starts as a small defects in the coating layer and spreads till causing structural weakness.

2.2.3. GALVANIC CORROSION

It occurs when specific condition between two different metals exists. These two metals have to be electrically in contact and immersed into an electrolyte. If a difference in electric potential exists between the two metals one of them become the anode while the other becomes the cathode. At this point a galvanic couple is formed and an electrochemical reaction starts: the anode get corroded and the cathode remains preserved; the bigger the potential difference is the quicker the reaction will be. In general the anode will corrode faster than it would alone, in favor of the cathode so it is called the sacrificial element.

2.2.4. ENVIRONMENTAL CRACKING

Environmental cracking is a corrosion process characterized by a such a rapid progression which once initiated can lead the metal to a catastrophic failure almost immediately. It originates from a combination of chemical, temperature and stress-related conditions; more in detail, in case of pipelines, it occurs when the effect of corrosion combined with tensile stress affects a ductile material, leading it to a brittle fracture. The following typologies belongs to environmental corrosion: *stress corrosion cracking* (SCC), *corrosion fatigue* (CF), *hydrogen-induced cracking* (HIC) and *liquid metal embrittlement* (LME).

2.2.5. FLOW-ASSISTED CORROSION

Also known as flow-accelerated corrosion, it occurs when a protective layer of oxide, existing on a metal surface, is removed by the action of a fluid flow such as wind or flowing water. In our case this mechanism can also happen at the internal wall of the pipe by the combined action of the product flow and corrosion. What happens later is that the oxide removal exposes the underlying metal to corrosion and, once new corrosion products form, the damaging sequence may be repeated generating, for example, grooves on the internal pipe surface. The existing form of flow-assisted corrosion are *erosion-corrosion*, *impingement*, and *cavitation*.

2.2.6. INTERGRANULAR CORROSION

Intergranular corrosion is a chemical or electrochemical deteriorating reaction occurring at the scale of metal’s grain. It is caused by the presence of impurities in different concentration in the metal, particularly near grain boundaries respect to the rest of the material, or by the strain energy of misalignment of atoms in the grain boundaries.
In these conditions grain boundaries assume anodic behavior respect to the surrounding grain material so to result more vulnerable to corrosion then the bulk of the metal.

2.2.7. DEALLOYING

Also known as selective leaching, dealloying consists in a selective corrosion of a specific element in an alloy where one of its constituent is "removed" preferentially leading to an altered and irremediably weakened residual structure. The mechanism behind dealloying is a galvanic reaction due precisely to the existence of different elements in the alloy: it happens that one element assumes the role of the anode respect to another which acts as the cathode. The anode, which starts deteriorating, is the element which is literally "pulled out" of the alloy.
The most famous type of dealloying is the de-zincification of unstabilized brass resulting in a deteriorated and porous copper structure.

2.2.8. FRETTING CORROSION

This deterioration mechanism occurs as a result of repetitive wearing, weight and/or vibration on an uneven and rough surface, or slip at the interface between two surfaces in contact. It can generally develops in rotation and impact machinery as well as in bolted assemblies, bearings and surfaces who suffered the effects of vibrations and rubbing during transportation. What exactly happens is that movements between surfaces can scratch away protective layer and facilitate the eventual scratching action operated by corrosive products which removes material from the surface.

2.2.9. HYDROGEN ATTACK

Hydrogen attack can occur if hydrogen molecules are somehow putted in contact with a metal during coating, plating , forming, cleaning and finishing operations. "With time passing hydrogen atoms diffuse through the pipeline steel by breaking and re-forming molecular bonds, generating characteristic blisters or filling the air space between and the outside pipeline wall in sour service. As hydrogen gas builds in the annulus, the pipeline wall, especially if it is thinned by other defects, can implode inward creating multiple problems."
"Hydrogen blisters are however much more common in pressure vessels than in pipelines in sour service." [1](Piping and Pipeline Assessment Guide, A Keith Escoe, 2006).

2.2.10. HIGH-TEMPERATURE CORROSION

"This type of corrosion occurs due to chemical reactions resulting in the deterioration of metals at high temperatures" [1](Piping and Pipeline Assessment Guide, A Keith Escoe, 2006). It can also be caused by high-temperature oxidization, sulfidation, and carbonization.

2.2.11. MECHANICAL DAMAGE DURING EXCAVATION

During the existing life of a pipeline a common damage sequence is represented, particularly for buried pipelines, by excavators hitting the pipe with their shovel or simply bumping it with their body. This incidents are caused both by pipeline operators or other unrelated companies that find themselves operating in the vicinity of the pipeline path. Two types of defects are usually considered when we talk about excavation damages: *gouges* and *dents*.

GAUGE
Usually we talk about gauge when a whatever object mechanically remove (or relocate) a portion of material from the surface of a component, generating a local reduction of the material thickness or a local thinning of pipe wall in our case. Geometrically a gouge is characterized by a length greater then width, resulting so with an elongated shape. Another feature is that the material removal occurred by a cold working.

DENTS
Like gouges also dents can be generated by the same sequence of events, so when the pipe is hit by a shovel during excavation. The main difference is that for dents, material removal or scratching on the pipe surface does not occur; what does occur is a deformation of the pipe wall, generally inward.

2.2.12. RUPTURES DUE TO NATURAL CATASTROPHIC EVENTS

Damages or flaws caused by natural catastrophic events includes a variety of typologies ranging from superficial defects to substantial ruptures which compromise totally the functioning and the safety of the pipeline system. What bond them is the cause which can be an earthquake, a storm, lightning, heavy rains, floods, strong wind, hurricanes or extreme and unexpected temperatures

3. Prevention

3.1. MATERIAL SELECTION

In order ensure the pipe to withstand the internal pressure during normal (or extraordinary even if calculated) working regime, structural characteristic of the pipe such as the material and wall thickness must be properly selected.

The choice of the material employed for pipeline construction is made considering multiple factors such as product to be transported, daily flow rate, operating pressure, characteristics of location and environment where the pipeline will be installed and types of construction techniques. Selection and design of materials used for pipeline and components also must observe guidelines dictated by API codes and recommended practices. Steel is by far the most used material for pipeline and components such as valves, fittings, metering, pumps and compressors. It is employed for pipeline which have to work at a pressure equal or higher to 100 psig and its convenience is due in fact to its high pressure resistance, strength and long operating life cycle. HDPE, PVC or fiberglass pipes are chosen in some case for low-pressure gas gathering pipelines, in hydraulic distribution field or other applications but these are not our concern since our focus is on hydrocarbon products transport pipelines employed for crude oil, refined petroleum products, LPG and natural gas.

Given the nature of the transported fluids, corrosion phenomena can develop on the pipe's internal wall; for this reason a specific analysis is required to determine which metallurgic additional component have to be present into the steel alloy to limit internal corrosion over time eventually together with the action of corrosion inhibitors injected into the stream. Another fundamental factor to be taken into account in the choice of material is the grade of steel. What can be said in general is that a high grade of steel leads to a high specified minimum yield strength *SMYS* so to a higher maximum allowable operating pressure MAOP. Nevertheless, given the hydraulic transport requirements, the choice of steel grade, pipe diameter, wall thickness, and operating pressure has not a unique design solution. For this reason the steel grade is determined through an economic comparative evaluation which allows to individuate the most economic steel grade in relation to pipe diameter, wall thickness and so strength requirements. Usually the result of these evaluations suggest that the employment of a higher grade of steel and/or a greater wall thickness and to operate at a higher pressure is less expensive than the choice of a larger pipe diameter and a lower operating pressure.

Particular attention must be paid to the choice of pipe material in case extreme operating temperature are considered. These comprehend cases of pipe installed above the ground where ambient temperature goes below $32°\mathrm{F}$ ($0°\mathrm{C}$) as well as buried pipe where the ground temperature goes below $32°\mathrm{F}$. Also attention must be paid to pipeline and its component in case the fluid to be transported requires a temperature lower than $32°\mathrm{F}$ or higher than $100°\mathrm{F}$, but this is not our concern since these temperature are out of the temperature range of transport hydrocarbons mentioned before.

3.2. MAXIMUM ALLOWABLE OPERATING PRESSURE

To make sure the transported product is able to flows from the delivery point of the pipeline till its end an adequate amount of energy must be guaranteed. Regardless energy is provided by external pumping stations or by a fully gravity-based flow system, this equals to say that fluid must be under a sufficient pressure to balance pressure loss effect due to fluid friction against pipe wall as well as elevation changes along the pipeline path. Of course, once the minimum pressure has been determined, it is necessary to establish upper pressure limits for ensure mechanical resistance of pipe and components. The allowable internal operating pressure in a pipeline is defined as “the maximum safe continuous pressure at which the pipeline can be operated without causing rupture” [1](Piping and Pipeline Assessment Guide, A Keith Escoe, 2006) which is generally known as maximum allowable operating pressure (MAOP).
What makes this pressure safe is that within this threshold value stresses occurring in pipe material are lower than its *yield strength*.

How we can observe in Figure 1. the consolidated practice in hydrocarbon transport field considers a pressurized fluid pipe is subjected just to two over the three directional stresses a tubular section can experience. This is justified by the fact that *radial stress* becomes significant only in pipes characterized by a thick wall but since almost the totality of transport pipelines are considered to have a thin wall stress in radial direction is neglected.

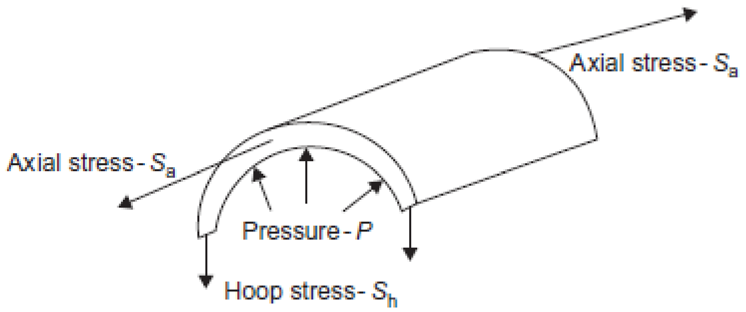


Figure 1. Stresses acting on a pressurized pipe

Thus *circumferential* (or *hoop*) stress S_h and *longitudinal* (or *axial*) stress S_a are the two parameters influencing pipeline capacity to withstand internal pressure. Particularly, since the hoop stress S_h is equal to twice the axial stress S_a , it’s the hoop stress that controls the internal pressure the pipeline can be loaded with. In case the pipeline is going to be designed for liquid transport the hoop stress can’t exceed a maximum value equals to 72% of the *yield strength* of the pipe material.

A fundamental operation in this sense is to perform the so called Hydrostatic Test which have the double aim of testing the pipe for internal pressure resistance and testing the hydraulic sealing (absence of leakage) prior to use, as it will be better discussed in Paragraph 3.5.
This test consist in filling a limited pipe section with water, pressurizing it till the required *hydrostatic test pressure*, maintaining pressure for a specified number of hours and inspecting the pipe for leakages. Then water it’s moved to the next pipe section and a new test starts.

From the point view of pressure threshold, Hydrostatic Test aims to ensure that the pipeline can be safely operated at a specific MAOP, by testing the pipe at test pressure higher than MAOP. For a better comprehension we can take the example of a pipe tested above the ground.

In this case the *hydrostatic test pressure* must be higher or equal of 125% of the MAOP which is controlled by the hoop stress S_h . By its side S_h is equal or lower to 72% of the *yield strength* of the pipe material so during the test the pipe will experience a hoop stress S_h equal to $1.25 \times 0.72 = 0.9$ times the pipe yield strength.

In practical terms, in case of a liquid pipeline under normal operating conditions MAOP corresponds to a hoop stress $S_h = 72\%\, SMYS$ (which is Specified Minimum Yield Strength), whereas in case the pipe is being tested MAOP corresponds to $S_h = 90\%\, SMYS$.
Obviously test pressure and other settings are specific for the type of fluid to be transported as well as to the position of the pipe as specified by CFR regulations mentioned in the later chapter.

3.3. PIPES TRANSPORT AND INSTALLATION

Construction of a pipeline is a strictly sequential process that, like in an assembly line of a factory, must follow a rigid progression of events. Such a precise scheduling and execution aims both to respect construction schedule plan, so agreements between service companies and contractor, and to minimize risks of interference between the numerous operating crews so that damages to pipe joints and components are can be avoided. In particular there are some construction phases where specific attention is dedicated for avoiding joints and components to be damaged during operations or by external occurrence.

3.3.1. PIPE JOINTS TRANSPORT AND STORAGE

The general principle to be followed in order to protect pipe joints integrity before installation is to minimize the number of handling and to perform transport, loading/unloading and storage operation in the safer way possible. Pipe joints are delivered directly from the manufacture factory to the construction sites: transport is made by rail to a rail off-loading yard strategically chosen respect to the construction site. From there they are transported by truck to predetermined storage yards located along the construction corridor. Numerous storage yards and construction yards may be implemented to support pipeline construction and, depending on the rail delivery schedule, trucks will make continuous trips between off-loading areas and pipe storage areas until the number of joints assigned to each storage area has been delivered.

In addition to their primary purpose of temporary pipe storage, these yards can be used for the so called *double jointing* operation if the construction site make it conceivable and where permits allow. In this case couples of joints are welded together inside the yard and set down on a double-joint rack; later they will be trucked to the corridor. The advantage brought by this method is that many welds are performed in more favorable conditions compared to pipe corridor's ones, allowing also to safe time. Further storage yards are implemented to host equipment, materials as well as key essential items.

3.3.2. STRINGING OPERATION

Once the trench has been completed can be deployed along the corridor. Thanks to the relative proximity between storage yards and corridor stringing trucks have only to haul joints from the storage to the relative stretch of the corridor where it will later bent and welded alongside the trench. In this way each truck will cover only the portion of the corridor belonging to a single storage yard from which it takes the joints: as a result traffic will be limited along the corridor reducing so the risk of damaging pipe joints. Who fulfill the whole operation is stringing crew, which is responsible for loading pipe joints onto trucks, hauling to the corridor, off-loading and stringing pipe onto skids alongside the trench.

3.3.3. LOWERING-IN AND BACKFILL OPERATIONS

This procedure can starts after the pipe has been tied and welded, the scraped coating has been restored, and hydraulic test has been successfully performed. In that moment the whole pipe lays on skids, then a portion of the pipe is secured with a number of roller equipped hearnesses and lifted up by side-boom tractors which position the pipe above the ditch. These tractors are arranged in a row; they starts to cover the corridor gradually lowering the pipe to the bottom of the trench as they pass. It is necessary to ensure the surface where the pipe is laid does not present asperities and, in case of solid rock or rocky soil ,it is suggested to recreate a fine soil bed to prevent pipe and pipe coating to be damaged.

At this point trench can be backfilled: backfilling and bedding must be provided in a manner to guarantee firm support for the pipeline and avoid to damage pipe coating and the pipe itself by backfill material or subsequent surface activities. Subsoil stockpiled during digging operation is placed underneath and above the pipe taking care about the possible presence of rocks or hard lumps; then top-soil can be placed above. Attention must be paid in order not to cause distortion of the pipe cross section which could compromise the passage of internal maintenance and inspection devices.

3.4. WELDING E NON DESTRUCTIVE TESTING

Welding plays a major role in the construction, modification, and repair of hazardous liquid pipelines and gas pipelines, thus particular attention is given in order to guarantee high efficiency and integrity of welds. To achieve this, suitable and carefully specified welding procedures are employed by qualified welders, and successive nondestructive tests are effectuated.

3.4.1. PIPELINE WELDING PROCEDURE

Pipeline welding procedure are regulated by section 5 of API 1104 which is the pipeline welding standard for weld quality and innovation. This expressly requires that the welds be made by a qualified welder. In addition, before any welds is allowed to be performed, API code strictly requires a *qualified welding procedure specification* to be drawn up Figure 2.
This last is a detailed document which demonstrates that the selected welding process lend to the pipeline suitable mechanical properties such as hardness, ductility, strength and soundness.

As you can imagine it is necessary to carry out test, particularly destructive tests on pipe weld specimens such as tensile strength test, nick-break test, root-bend and face-bend tests, and jig guided bend test, to qualify a suitable welding procedure. Also in this the code is very clear, in fact it specifies in details the number of specimen required, details necessary to prepare weld specimens for testing as well as test method for each test and test passing criteria.

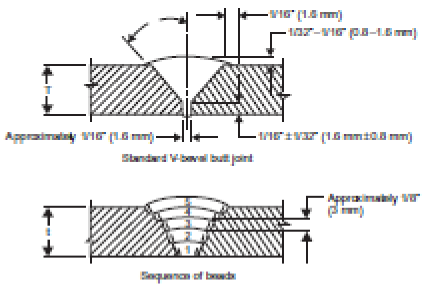
For example, if we consider *tensile strength test,* criteria for weld acceptance requires for each specimen that tensile strength of the weld and the fusion zone must be greater or equal to the SMYS of the pipe material. In practice this can be verified by the fact that once the specimen is loaded it shall breaks in the parent material, so outside the weld and fusion zone.

Reference: API Standard 1104

PROCEDURE SPECIFICATION NO. ________________

For ________________________ Welding of ______________________ Pipe and fittings
Process ____
Material ____
Pipe outside diameter and wall thickness ______________________________________
Joint design ____
Filler metal and no. of beads ____
Electrical or flame characteristics ____
Position ____
Direction of welding ____
No. of welders ____
Time lapse between passes ____
Type and removal of lineup clamp ____
Cleaning and/or grinding ____
Preheat/stress relief ____
Shielding gas and flow rate ____
Shielding flux ____
Speed of travel ________________ Plasma gas flow rate ___________________________
Plasma gas composition ____
Plasma gas orifice size ____
Sketches and tabulations attached ____

Tested ______________________________ Welder ________________________
Approved ____________________________ Welding supervisor ________________
Adopted _____________________________ Chief engineer ___________________



Note: Dimensions are for example only.

Electrode Size and Number of Beads

Bead Number	Electrode Size and Type	Voltage	Amperage and Polarity	Speed

Figure 2. API approved welding procedure specification form

3.4.2. WELDERS QUALIFICATION

According to API 1104, section 6.2 through 6.8 welders must be in possession of the qualification that qualifies them as suitable for carrying out specific welding procedures before any production welding is done. As previously mentioned this is one of the ways by which pipe constructor guarantee welds efficiency to reduce the risk of flaws or damages which could lead to leakage occurrence.

Welders undergo to specific examinations which determine their ability to make sound but and fillet welds applying the exactly qualified procedure specification discussed above (which are the same techniques they are gonna use on field). Examinations are conducted in presence of a representative observer designated by the company. In addition to be observed the welder have to produce a certain number of weld specimens, as required by the code, which have to meet acceptance criteria as the one mentioned in previous Paragraph about qualified welding procedure specification. Despite successfully passing qualification, welders will be trained and checked out by the company before using semiautomatic and automatic welding equipment.

3.4.3. NONDESTRUCTIVE TESTING OF PIPE GIRTH WELDS

Differently from weld specimens which undergo to destructive tests, welds made on pipeline to tie-in joints cannot undergo the same type of test for obvious reasons. To the purpose of testing pipeline weld integrity different type of the so called NDTs (nondestructive tests) such as X-ray, magnetic-particle, liquid-penetrate, ultrasonic testing and of curse visual inspection are implemented. Since almost all NDT are done by X-ray we can say it is the most important method. Radiographic inspection owes its success to its versatility; in fact it can be applied both on small and large diameter pipes during construction, maintenance and repair, it is particularly sensitive to IP and IPD defects and (inadequate penetration and inadequate penetration due to high-low respectively) and numerous other types of defect can be detected using it.

In other cases *Automatic Ultrasonic Testing* (AUT) is preferred, particularly in case of *automatic production welding* use. Its main advantage is in this sense its execution velocity. In fact it is able to perform a complete inspection and interpretation of a girth weld in just 90 seconds and can keep up with automatic welding rates, whereas an X-ray takes 10 minutes on the same weld.

3.5. HYDROSTATIC TESTING

Hydrostatic Test is an extremely important operation for many purpose included testing pipe strength and verify the presence of leakage or ruptures prior the use of the pipeline. According to regulations CFR Title 49, Part 195 and Part 192 concerning respectively Hazardous Liquid Pipeline and Gas Pipelines operators are not allowed to operate any pipeline or new segment unless they have been successfully hydrostatically tested. Furthermore the prescription includes also segments of pipe which have been replaced or relocated. The test can be performed on hazardous liquid or gas pipeline still lying above the ground as well as new or in use pipeline which have been buried already with some procedural difference.

Hydrostatic test can be started not before other fundamental operation are successfully completed: complete tying-in of welds, X-ray test on welds, restoration of the coating previously scraped away to weld and, if planned, backfill of the trench. At this point the pipe is divided into test sections, each between two block valves, having a length determined in accordance to the pipeline elevation differences. Block valves are usually equipped with body bleeds in order to eliminate the risk of leakage. Now the pipe have to be filled with water, most likely coming from a nearby water source. While a pig or a sphere is pushed through the pipe section to displace all the air which, being highly compressible, would compromise test results filtered water completely fill that segment.

In case the pipe is above the ground or in an open trench regulation at Part 195 states that the section has to be pressurized to a pressure equal or slightly higher to 125% of the MAOP (maximum allowable operating pressure) and this value must be maintained constant for 4 hours minimum. Buried pipelines require instead to be subsequently maintained at a pressure equal or higher to 110% of the MAOP for an additional 4 hours interval. MAOP is equal and mandatory not higher to the internal design pressure which is determined by the hoop stress formula as follow:

$$P = 2 \cdot t \cdot \left(\frac{SMYS}{\mathrm{D}}\right) \cdot E \cdot F \qquad (1)$$

where

P is the Pipe internal design pressure (psi)

T is the pipe wall thickness (in)

$SMYS$ is the Specified Minimum Yield Strength of the current pipe (psi)

D is the pipe outside diameter (in)

E is the pipe seam joint factor, which is 1.0 for seamless or post-1970 ERW pipe

F is the Pipe design factor equal to 0.72 in general case or 0.60 to lower values for off-shore pipeline and other special case

Pressurization is an extremely delicate operation which requires personnel of the testing crew to be properly trained and informed about risks and dangers of subjecting the pipe and the transport system in general to an excessive pressure. It can lead to yielding and plastic deformation of the pipe wall, damaging of flange gasket, fittings and valves even to a pipe wall rupture.

Moreover overpressure is avoided also when the pipeline is operating: pressure must not exceeds MAOP to ensure a sufficient safety margin and to comply with federal code.
Since pressure surges can be a cause of overpressurization as a consequence of upset or unsteady state regime, pipelines are equipped with pressure relief valves and high-pressure switches to limit pipeline pressure to a maximum of 110% of the MAOP and assure safety conditions. In addition to internal pressure other parameters such as pipe wall temperature, test water temperature and ambient air temperature are monitored for the entire duration of the test.

3.5.1. NOT BURIED JOINTS

In case the pipe is not buried the eventual leakage is detected by visually inspecting the pipe section for its whole length and the nearby ground looking for water loss: the line riding personnel must continuously patrol the pipeline right-of-way staying in communication with the test responsible. If the outcome is negative the section passed successfully the test. Due to the variability of the ambient condition, some phenomena such as sun heating or ambient temperature change can require the bleed off of some test water in order to control the pressure and avoid maximum pressure to be exceeded. For the same reason an injection of water can be necessary at a certain point to balance the effect of an eventual ambient air cooling and so keep the pressure at test value. The two previous statements are valid both for buried and not buried pipeline. Water injected or released in these cases do not need to be measured since the leakage is detected visually.

3.5.2. BURIED JOINTS

For obvious reasons to determine result of the test is much more difficult in case of buried pipe. A common practice to help the eventual leakage detection is to add a green dye to the filtered water so the colored water will be easier distinguishable if emerging from the ground; the certain presence of a leakage, and so of a failure in the system, is however advised by an instantaneous pressure drop in the tested section. In case the leakage is quite small the detection is even more difficult and could be misdiagnosed whit high compressible air bubbles not displaced before the water injection. For this reason testing buried pipes requires sophisticated instrumentation and eventually a post leak analysis despite the principle of the test is simple. Once the current section has been tested the water is pushed down the pipeline and used to test the following section and so on.

3.5.3. TEST'S MEASUREMENTS

In addition to internal pressure other parameters such as pipe wall temperature, test water temperature and ambient air temperature are monitored for the entire duration of the test. A further measured parameter is the test deadweight which readings have to be taken and recorded at least every hour for the whole test duration including the start and the termination. In such a way, if injection or bleeding is required to keep the pressure within the test range, volumes of water added or subtracted and their exact times will be measured and recorded on the Hydrostatic Test Results and Data form show in the Figure 3. This form along with the different pressure and temperature recording charts will be attached to Test Plan and Pipeline Profile as official documents and kept for the entire life of the pipeline.

LIQUID PIPELINE SAFETY
HYDROSTATIC TEST RESULTS

PIPELINE DATA — Test Date

Pipeline Operator	Company conducting test if other than operator

Kind of Test
[ ] New [ ] Replacement [ ] Annual [ ] 3 Year [ ] 5 Year [ ] Other

Pipeline Identification (line number, name, etc.)

Pipeline Location (milepost, street, station, etc.)
From: __________
To: __________

Normal Product Transported	Normal Operating Pressure P.S.I. at (location)
Maximum Operating Pressure P.S.I. at (location)	

PIPE DATA

Pipe O.D.	Wall Thickness	Specification & Grade (SMYS)	Length of Pipe Being Tested	Volume (Barrels)

TEST DATA

Test Medium [ ] Water [ ] Petroleum*		*Has waiver been granted?	
Location of Pressure Recording Equipment		Elevation	
Other Elevations	Pipeline – High Point	Pipeline – Low Point	
Test Equipment	Make & Model of Deadweight Tester	Serial #	Date Last Calibrated
	Make & Model of Chart Recorder	Serial #	Date Last Calibrated
	Make & Model of Temperature Recorder	Serial #	Date Last Calibrated

Figure 3. Hydrostatic test and pipeline data form

3.5.4. POSTTEST RESULTS

SUCCESSFUL CASE: In addition to the absence of unequivocal water losses or rapid and important pressure drops, internal pressure must have been remained within the acceptance range to declare the test as successful; if yes the next section can start to be tested. Test pressure head and water supply connections and its pump are removed and mounted on the next section so valves are operated to transfer test water to a water treatment tank or to the next section depending if the test have to be performed on a single pipe section or on a whole pipeline respectively.

UNCERTAIN CASE: If the internal pressure decreased to values out of the tolerable range, requiring water injection to be brought back into, the test is not necessarily failed but needs to be further investigated by test engineer comparing data measured and recorded during the test with diagnostic tool such as ΔV/ΔP method. A possible case could be represented by pressure-time profile not trending with temperature profile of test water: this may indicate the existence of a small leakage. A pressure which was holding and suddenly dropped is instead a highly probable case of rupture.

3.5.5. POSTTEST LEAK ANALYSIS - ΔV/ΔP Method

This simple technique consists in taking measurements of volume and pressure intervals and compare them with the correspondent calculated ideal intervals to verify, for example, the presence of residual gasses or air trapped into the test section. During the first pressurization stage water injection can be stopped at an internal pressure of 50 psig or more and pressure and volume reading can be recorded. Then the procedure establish a bleeding of 10 psi followed by the measurement of the new pressure and volume data once the pressure stabilizes (volume data must be expressed in gallons). At this point ΔV/ΔP value is easily obtained dividing the measured intervals. It's strongly suggested to repeat this procedure and calculate a further 10 psi-based ΔV/ΔP value before the discharging the test water at the end of the test. Once real ΔV/ΔP values are fixed theoretical ones can be determined by the following formula:

$$\frac{\Delta V}{\Delta P} = V\left[\left(\frac{\mathrm{D}}{E \cdot t}\right) \cdot (1 - \mu^2) + C\right] \tag{2}$$

where

V is fill volume of the pipe section for an individual diameter (gal)

D is the outer pipe's diameter (in)

E is the elastic modulus of the steel pipe equal to 30000 psi

t is the pipe wall thickness (in)

μ is the Poisson's ratio of the steel pipe equal to 0.3

C is the water compressibility equal to $3.20 \cdot 10^{-6}$ in^3/psi

Theoretical ΔV/ΔP represent the volume for an associated change in pressure, for the specified volume of the test. If air is trapped into the current pipe section the real measured value will result larger than the ideal one. In these cases air must be vented before continue the test and the cause of its must be identified.

A further point which deserves to be mentioned is concerns a noticeable difference between testing liquid and gas pipeline which is that for the latter a cleaning and drying to 0°F dew point is required after test and test water removal. Other cases which procedure differs from the one described above are some section repair or replacement or short relocation: they can be tested with air, natural gas or inert gas in such a way that water removal and pipe drying can be avoided.

3.6. CORROSION CONTROL

Some of the most crucial activities actuated to the purpose of damages prevention and integrity safeguard of pipelines so to extent considerably the life of the pipeline are Corrosion Control actions. Every pipeline, whether buried in the ground or laying above the ground, or even submerged in water, is subjected to specifics deteriorating actions of the surrounding environment which affects welding, pipe coatings and of course pipe material itself.
Since corrosion phenomena are due to the interaction between the pipeline and the environment with its own specific characteristics, suitable corrosion protection solutions have to be evaluated case by case. For the mentioned reasons the design of corrosion protection actions starts from an accurate investigation of the environment which will host the pipeline: this mainly consists in a measurement campaign to determine soil to pipe electric potential and soil resistivity at various point along the chosen pipeline path as well as air characteristics, particularly moisture, pH and chloride salts presence.

The research of a suitable corrosion control (CC) strategy leads to combination of techniques usually consisting in external pipe coating, internal lining, sacrificial anodes or impressed current. In order to ensure CC program correctly works and maintains its efficiency over time each technique must be properly applied and an adequate maintenance plan must be implemented and actuated. To these purposes a fundamental aspect is that operators employed both in realization, assessment and maintenance phases must be adequately trained on corrosion control.

Over the existing corrosion control techniques four common method used on pipelines can be individuated as follow.

3.6.1. PROTECTIVE COATINGS

Anti-corrosion protective coatings comprehends two different categories: *External Pipe Coatings* and *Internal Pipe Coating* (*Liner*).
As you can imagine the first type is used for the *cathodic protection* (CP) of external pipe's surface. This coverings applied on the pipe parent material act as a barrier isolating it from the surrounding environment. Many types of coating and materials exist on the market in order to fit the specific environmental conditions and customer requirements but they can be substantially summarized in four groups as follows:

1. Epoxy resins such as FBE (fusion-bonded epoxy) or polyester materials
2. Bitumastic materials such as coal tar, asphalt, or bitumen applied on iron, steel or concrete pipes
3. Tape-like coatings literally rolled-on the pipe, whether naked (uncoated) or with a preexisting coating
4. Shrink sleeves applied locally on welded joints where the preexisting coating has been scraped away to allow welding procedure, as previously mentioned in the Paragraph concerning welding.

Some of these coatings are applied directly on field, particularly in case of maintenance operations when damaged coating have to be restored or like in the case of shrink sleeves, whereas most of them are applied in workshop by specialized company before pipes to be transported on the construction field.

Application techniques generally ranges from brushing to rolling, spaying and dipping, additionally it has to be known that almost the totality of existing coating types are multilayered through the overlapping of different isolation materials. Application is a very delicate phase, and this is proved by the fact that most of coating failures originates from a defective (even locally only) surface preparation such as the presence of contaminants left on the surface or an inadequate sandblasting.

Internal Pipe Coating usually referred as *Lining* is motivated by different reasons. It aims to isolate the pipe parent material from the fluid transported, which in case of hydrocarbon product is characterized by a chemical aggression to the pipe wall. It allows so to prevent (or at least to delay) the caustic and abrasive action caused by the product flow; additionally it improves flow efficiency by reducing friction with pipe wall. As in the previous case also pipe Liner can be made of different material depending on the fluid characteristics and operative conditions, and it is mostly applied in workshop by specialized company. What does differs a lot from External Coating is maintenance technique: in case refurbishment is required the pipeline does not need to be disassembled because the coat of liner can be applied by a specially designed Pig which literally spreads the paint-like liner on the inner surface with its gaskets by passing through the pipe.

3.6.2. CATHODIC PROTECTION (CP)

CPs, also referred as active protection methods, are techniques which basing on electrochemical principles allow to prevent or slow down corrosion rate on metallic structures located in aggressive environments. The metal to be protected is brought the closest possible to an immune state by reducing its corrosion potential. This is realized by applying a direct electric current (DC) traveling between an electrode, called *anode,* and the metal to be protected, called *cathode,* so to counterbalance the normal corrosion effect caused by the potential difference between the "precious" metal and the electrolyte material where it is immersed into (in our case the pipe and the soil respectively). This particular electric circuit known as *Electrolytic Cell* and schematized in Figure 4. ensures that the *anode* gets corroded instead of our *cathode*.

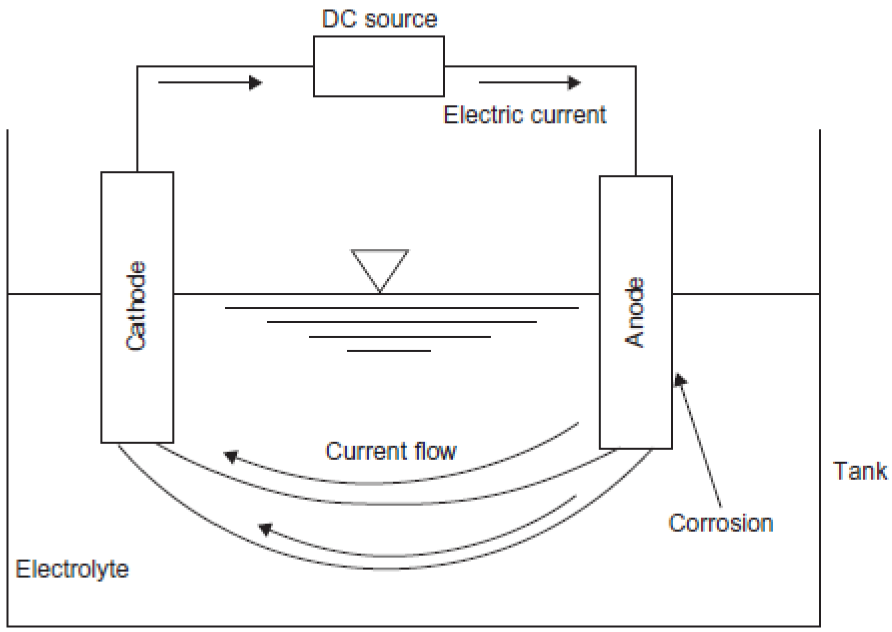


Figure 4. Schematic of an electrolytic cell

Cathodic protection can be realized through two different modes which are the impressed current system and the sacrificial anodes system as explained below.

3.6.3. IMPRESSED CURRENT PROTECTION

This method, also defined as active system, relies on a DC source to supply the required current. As we can observe in Figure 5. the positive terminal of the rectifier is connected to the soil by a ground plate which must be an insoluble electrode (anode) whereas the negative terminal is connected to the buried pipe (cathode). The steel pipe protection is ensured by the *e.m.f.,* applied by the rectifier, which generates a properly set current able to counterbalance the other *e.m.f.* which couses the galvanic current responsible for the corrosion phenomenon.

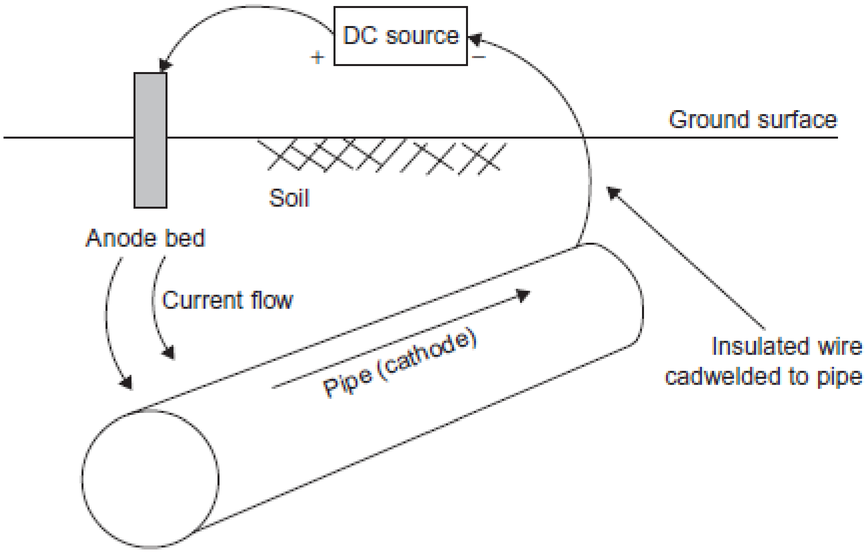


Figure 5. Schematic of an impressed current protection system

In the specific field of Oil and Gas pipelines the anode usually consists of a copper sulfate electrode which requires to adjust the DC source in such a way to maintain the soil to pipe potential to a value equal to $-0.85\ V$.

One advantage of this system derives from the use of anodes made by noble metals which wear out slowly so to guarantee a certain durability, conversely a weak point of this system is the relatively high energy requirement. What is fundamental to the reliability of the system is the planning of a monitoring campaign to assess corrosion rate both to verify efficiency of the Cathodic Protection system and the health of the pipeline.

3.6.4. SACRIFICIAL ANODES PROTECTION

This method relies on the properties of the *Galvanic Cell*. Such a system is made by two different type of metal having different electric potential which are connected among them and immersed into a proper electrolyte. The metallic element characterized by the most negative electric potential will be the sacrificial anode, enduring the totality of the oxidization so to protect the metal with the less negative potential, which in our case is the pipe.

As we can observe from the schematization in Figure 6. the circuit constituted by pipe, sacrificial anode, conductor wire and the soil will generate a spontaneous flow of negative electric charges from the anode to the cathode.

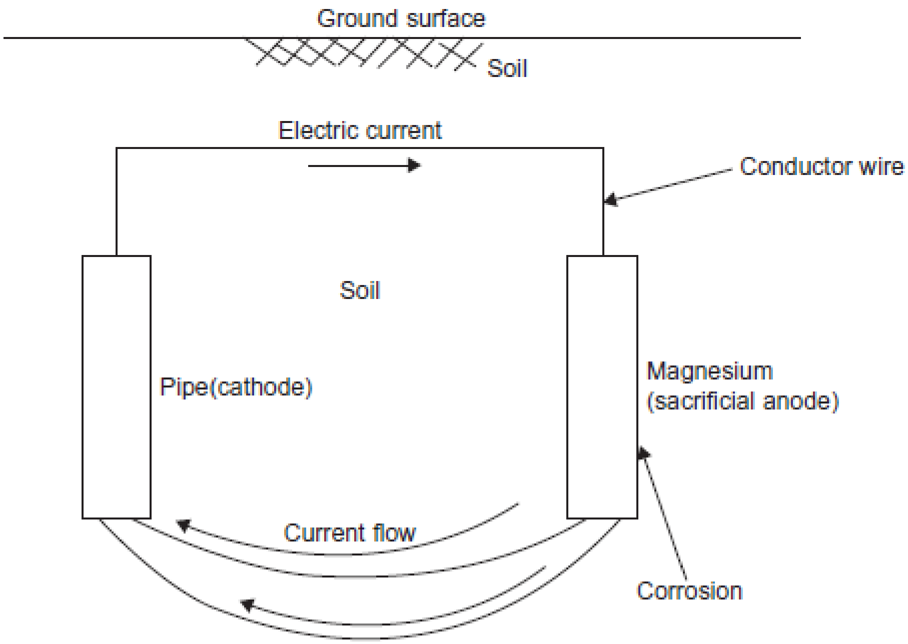


Figure 6. Schematic of a galvanic cell protection system

The result of this passage of charges will be that the zinc or magnesium electrode will get corroded whereas the pipe integrity will be preserved. The main advantage of this method consist in the spontaneity of the chemical reaction so in the absence of an external electric source.

3.6.5. MATERIAL SELECTION AND DESIGN

A factor of great importance in the field of the actions actuated to mitigate the deteriorating effects of corrosion on pipelines is the use of suitable materials. A particular attention must be dedicated to the selection of the proper material for each specific application. In general terms the material categories used for their corrosion-resistant properties are stainless steels, plastics and special alloys combined with the pipe. Material selection as well as their applicative design shall be done considering the designed useful life of the pipeline without neglecting aspects related to the surrounding environment, maintainability, and availability of spare parts and materials over years.

3.6.6. CORROSION INHIBITORS

These techniques, which deserve at least to be cited, consists in the application of additives such as acid, cooling waters, and steam to decrease the corrosion velocity when added to the environment. They perform their action by forming thin films on the metal surface.
In alternative other types of corrosion inhibitors are suitable to be injected directly into the flow stream to reduce the amount of internal corrosion.

3.7. CORROSION COUPONS

A corrosion coupon is a simple and very effective tool used on the pipeline when this last is subjected to the corrosive action of the transported fluid. To be more precise it is used when the transported fluid has certain chemical properties which, if combined with that specific pipe material, make the fluid particularly aggressive towards the internal surface of the pipe, as well as towards valves and other components of the pipeline system, corroding them over time.

These tools, consisting of metal samples made of the same parent material of the pipeline and secured on a proper support , are placed in contact with the fluid for the purpose of monitoring the corrosive properties and estimate their progression rate. Each coupon is inserted inside the pipeline, immersed into the fluid stream in a well selected position which ensure the coupon to not block or disturb eventual Pig passage as can be a facility. Once installed the coupon is periodically removed and analyzed during the year so to provide valuable data from were an estimate of life expectancy of materials can be obtained. The systematic use of coupons turns out to be beneficial in terms of repair costs, maintenance, and measurement of material failure. Conversely uncontrolled internal corrosion phenomena can easily degenerate causing pitting or pipe wall thinning which can eventually lead to leak occurrence.

3.8. PIPELINE MARKERS

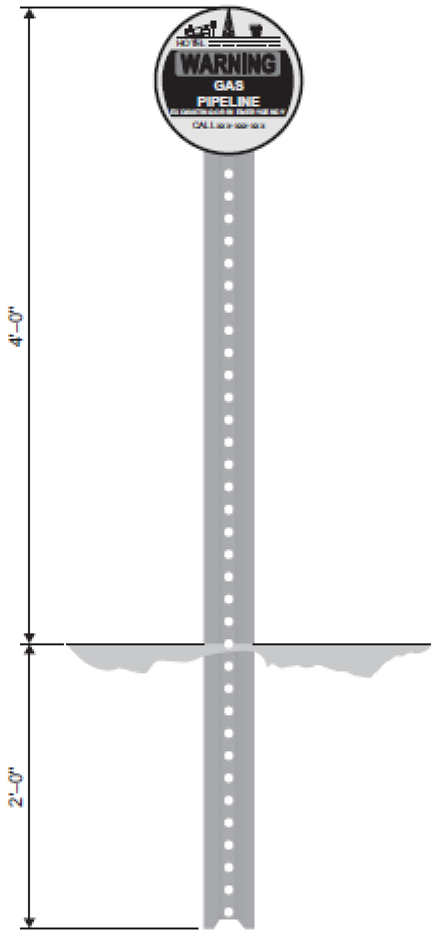
It is a specific signage used along the pipeline path to signal the presence of a pipeline, provide warning information and identify the location of each marker by a serial number.
Three types of markers generally exist:

- Markers placed along the pipeline route
- Areal markers
- Water crossing markers

Between the different goals of markers in this paragraph we will take into considerations those aiming to prevent the pipeline to be damaged by unrelated operating companies or privates unaware about the pipeline presence.

Markers belonging to the first type are installed at locations along the pipeline to mark the pipeline path and warning that a pipeline is present there, so if privates or a company plans to do any work in proximity of the pipeline they will be aware. By contacting pipeline operator they can obtain detailed information about the location and the depth of the pipeline allowing to prevent any risk to hit and damage the pipeline by excavation or works in general. Furthermore by contacting the local “One Call” office information about the presence of underground pipelines or utilities located in urban areas can be obtained.

The employment of markers is regulated by ASME codes B31.4, Paragraph 434.18 for liquid pipelines and B31.8, Paragraph 851.7 for gas pipelines. Codes clearly declare that pipeline markers shall be placed adequately with the aim of protecting the public, persons performing work in the area and the pipeline itself.
Particularly, in case the pipeline is buried, markers must be installed at each public road crossing, at each railroad crossing, at each navigable stream crossing. A sufficient number of them must be located along the remainder of the buried line, whereas in case the pipeline runs above the ground markers are required in those areas accessible to the public. Signage must observe specific format as we can observe in Figure 7. as follows:



Typical pipeline warning marker
Not to scale

Figure 7. Typical pipeline marker

“The marker shall state at least the following on a background of sharply contrasting colors:

1. The word “Warning” or “Caution” or “Danger” followed by the words “Petroleum [or the name of the hazardous liquid transported] Pipeline” or “Carbon Dioxide Pipeline” all of which, except for markers in heavily developed urban areas, must be in letters at least one inch high with an approximate stroke of one-quarter inch.
2. The name of the operator and telephone numbers (including area code) by which operator can be reached at all times. “(E. Shashi Menon, Pipeline Planning and Construction Field Manual).

In case of gas transport previous statements are equally valid (the word “Petroleum” is replaced by “Gas”) as enunciated by B31.8, Paragraph 851.7 ASME code.
Furthermore it is fundamental to ensure the efficiency of signage system in time by maintaining markers and the surrounding right-of-way so they can be easily read and not obscured. API RP 1109 it’s suggested to be used for additional guidance.

In case of a pipeline crossing a river its presence shall be indicated by installing large signs on the shore of both sides of the river, in correspondence of the location where the pipeline is buried. The importance of these markers is particularly evident in case the river is navigable since the buried pipeline could be damaged by unaware boats dragging the anchor as well as by dredging operation.

4. Leakage Detection and Localization

4.1. Direct observation

4.1.1. PATROLLING

It is the simplest, at least in theoretical terms, and the more direct method to spot leakages. Operators inspect the pipeline covering the right-of-way both by foot and/or by helicopter or small aircraft. The traces they look for are: puddles of liquid product on the ground surface (appearing as dark stains if spotted from the sky), characteristic noise such as high-pitched sound caused by the high-pressure fluid flowing out the pipe, erosion of the ground surface in correspondence with a leakage of high-pressure fluid, and the distinctive smell of gas leaking out.
In particular the last one applies only to gas distribution networks where an odorant additive is injected into the main stream for detection and safety reason. Since this technique is not applied in distribution pipeline is not our concerns.

Patrolling the pipeline with the purpose of leakage detection can be done both on regular basis, so on scheduled intervals according to *Pipeline Monitoring Plan*, and in emergency case when a leakage alert has been transmitted by the other complementary monitoring systems. Of course the effectiveness of patrolling in the second case depends on pipeline length and on the number of operators in charge, since time required to locate the leakage is a critical factor, and as last on cleaning condition of pipeline right-of-way. Maintenance of the right-of-way to keep it free enough from growing vegetation helps operators in spotting leakages, therefore it’s a highly recommended practice.

Also markers have an important role in the success of patrolling operation: even though operators could be equipped with GPS tracker markers provides an easy and clear reference point to locate the leakage and report it to the pipeline operation center, especially for aerial patrolling.

4.1.2. UNOFFICIAL PIPELINE MONITORING

An help in pipeline monitoring is unintentionally performed by people living or working in the vicinity of the pipeline, who can inform pipeline operator in case they notice a leakage or problems in general with the pipeline. This is one of the main reasons why markers are used, in particular the first of the three types of markers mentioned in previous paragraphs.

Pipeline Markers have to be installed at exact locations along the pipeline and, according to ASME B31.4 Paragraph 434.18 for hazardous liquid and ASME B31.8 Paragraph 851.7 for gas, they have to clearly states also: the name of pipeline operator, telephone number and the identification area's code. In this way people can report the exact location of the problem.

4.1.3. TRACER GAS

Leakage detection by tracer gas originates from methodologies for ruptures detection in telecommunications pressurized cable sleeves. The functioning principle is based on injecting into the pipe a mixture of inert, nonexplosive and nontoxic gases which have to be lighter than air. At this point the gas mixture escapes through the rupture and operators try to intercept its presence and define the area interested by the gas loss. This technique can be employed both in hydrocarbon and water pipes with quite different procedures because of the need of using compatible types of gases and because of the diverse characteristics of pipelines.

HYDROCARBON PIPELINE

For oil or gas pipelines the use of tracer gas is adopted mainly for surveillance procedures and it is performed without interrupting the transport of fluid. A nontoxic odour gas such as mercaptan or some electrically detectable gas such as helium can be injected inside the main stream and improve surveillance effectiveness in general. Trained tracking dogs can be used to sense the presence of leaked gas patrolling the right-of-way: successful cases have been reported such as that of three tracking dogs which were able to locate 150 leaks in 9 days patrolling over a 150km long gas pipeline. However, in case of investigation performed in emergency conditions, the effectiveness of dog patrolling is quite scarce because a higher rapidity in detection is required. Another existing practices which use tracer gas for oil and gas pipeline applications are External Sensing Systems installed along the pipeline. These systems monitor the environment outside the pipeline and, like all tracer gas based techniques, their effectiveness strongly depends on weather conditions and wind direction. Two common ESS are vapor monitoring and liquid detection cable systems. Both these techniques require the construction of an impervious barrier beneath the pipeline to collect and accumulate the eventual loss of material: without fluid being accumulated the sensing system is not able to guarantee an early warning.

WATER PIPELINE

For water transport pipes it's a different scene: tools employed, gases and the operative procedure changes. In this context the technique is used for buried pipes; once injected, tracer gas have to rise up through the soil and once it reaches the surface it can be detected with the appropriate device. It is particularly recommended for small size leakages which cannot be detected with acoustic methods. At its origin, in early 70's, this technique employed a mixture of methane and argon which required a strict concentration control in order to be sure to remain below the methane LFL (LEL) which is about 5% in volume. Later, mixtures containing helium were adopted in telecommunication field while in the field of water transport hydrogen-nitrogen mixtures began to be used for obvious economic reasons since volumes of gas required are considerably larger. Also in this case concentration need to be carefully kept under control since hydrogen mixed to water results to be highly explosive. A common practice is to employ a mixture used in foundry applications containing 5% hydrogen and 95% nitrogen which remains below hydrogen LFL.

At this point the task is to detect minimum presence of gas on the ground surface. This can be done by a tool able to suck air sample by specific probe, analyze it and detect the presence of infinitesimal gas concentrations in the order of magnitude of few ppm, and display results to operators. From the first applications with methane, using flame ionization devices, an innovation step was done adopting semiconductor sensors, less selective but definitely cheaper and easier to use. Modern hydrogen detectors are highly selective semiconductor in terms of ppm: they must not to sense methane in order to prevent the detection of natural gas diffusions coming from sewers, peat bogs or gas distribution networks and so not to mispresent measurement. For concentration higher than 1% till 5÷7% thermal conductivity sensor are used. Other parts they are equipped with are an inner pump for sampling, acoustic alarm to warning operators of gas presence and backlit displays.

For pre-localization two type of probe exists: a *bell-probe* suitable for controls on short distances , cases of loose soil above the pipe or places located beneath stairs; *"carpet" probe* to sample without continuity solution long pipeline segments beneath a compact soil. *Tip probes* used for the exact localization by soil perforation normally have a conical tip which plugs the hole avoiding air suction which could alter sample composition leading to a wrong result.

WATER PIPELINE - OPERATIVE PROCEDURE

A significant difference respect to oil & gas applications is that the tracer gas is no more injected into the product flowing stream. The procedure provides that the pipeline segment to be inspected must be isolated and emptied before the injection of the gas. The injection occurs through a valve mounted on one of the terminals, such as a blind flange or a meter's fitting, while a vent must be opened at the opposite terminal to allow residual air to flow out the pipe. Controls at the injection terminal's pressure reducer are suggested to avoid the gas tank to freeze consequently to uncontrolled gas decompression. As the injection goes on measurements with a gas detector have to be taken at the outlet vent, to check when the isolated segment is saturated with gas. At that point the vent is closed and the pipe is pressurized. A variable time interval (tens of minutes to several hours) have to pass, depending on the pipe laying depth, to allow the gas to spread into the soil and rise up till ground surface.

Then the pipe path is covered by operator sucking air sample on the ground surface. Evaluation about mutual influence of type of gas used, diffusivity capacity, soil characteristics and knowledge of the pipe's path must be done to estimate how circumscribed the research area is. For example the use of hydrogen leads to very delimited research zone since it rise up quite fast and do not spread much in the subsoil. In presence of compact surface, like asphalt, concrete or stone flooring, "covering" perforation and use of tip probes is required to avoid the gas escaping through cracks or crevices far from the leakage point.

Once the maximum concentration point is located two holes, one downstream and one upstream, are realized symmetrically respect to it on the pipe path. Survey holes must be spaced about 70÷100 cm among them and must be 30÷50 cm deep and further air samples are taken from them. This technique is valid only for pipes fully buried in soil, is not applicable to pipes laying in tunnel or vertical segments.

4.2. *Online Pig-Based Method*

4.2.1. SMART PIGGING

A pipeline pig is device which acts like a free moving piston inside the pipeline, sealed against the inner wall by a number of rubber sealing elements. Pigs are widely used in oil and gas industry for operation and maintenance: several types and models exists each specifically designed for a certain type of application such as pipeline commissioning, cleaning, filling, dewaxing, batching and pipe monitoring.

Among these, *Smart Pig* is the typology which includes special equipped pigs suitable for leak detection or, more in general, for pipe internal inspection. Like the other typologies, a Smart Pigs operates inside in-service pipelines without the need to interrupt the fluid transport to the costumer.
During its motion it is able to detect, measure and record several types of anomalies either on the inner and outer pipe wall thanks to the different metering instruments they can carry.

4.2.2. SMART PIG TYPES

Four different typologies of Smart Pig basically exists, each equipped with technology which allows them to be specialized in inspecting and assessing specific anomalies rather than others; all of them aim at pipeline integrity assessment anyway.

The first is the MFL magnetic flux leakage pig, an electronic pig specially designed for identification and measurement of metal loss in the pipeline wall caused by corrosion both inside or outside the wall, gouges, etc. Metal losses are identified through the application of a temporary magnetic field: as the pig passes through the pipeline a dedicated device induces a magnetic flux in the pipe wall between the two magnetic poles present onboard. If the pipe wall is homogeneous and with no defects the magnetic flux distributes homogeneously too, while if metal losses are present it will result in a change in flux distribution; this last leaks out the pipe wall, we talk indeed of Magnetic Flux Leakage. Flux leakage is first detected and measured in terms of amount and distribution by sensors, later the signal is processed and the resulting data are stored onboard the pig to be later analyzed and reported once the pig is retrieved. The primary purpose of using an MFL pig is the detection of corrosion defects and the estimate of their size. The most recent MFL models are able to detect even defects of less than 5% of the wall thickness, so small not to be easily spotted visually. About crack detection MFL has a very limited capability: it may detect cracks in girth welds but it is not able to detect and locate the ones on longitudinal weld seam or, more in general, on pipe’s longitudinal axis which are the most dangerous.

The second type, the ultrasonic testing UT pig, is able to measure also pipe wall thickness in addiction to metal loss. It is equipped with transducers that emit ultrasonic signals orthogonal to the surface of the pipe. Once signals reach the wall, both the internal and the external surfaces generate an echo which goes back to the pig. The return times of signals are measured and compared with the speed of sound in the steel of the pipe, allowing to determine wall thickness. Cleaning of internal surface, removal of wax as absence of scale buildup turns out to be extremely important for the success of the UT test, especially for crude and heavy oil pipeline.

The third type is a modified version of the classic UT pig, called Shear Wave Ultrasonic pig. It was designed with the aim of realize a pig able to reliably detect longitudinal cracks in suspected pipeline, longitudinal ERW weld defects, and crack-like defects such as stress corrosion cracking. Since the pipe hoop stress acts directly on longitudinal cracks, a missed detection of a crack can ultimately results in rupture. For this reason this type is one of the most recommended for the purpose of leakage prevention and detection. This pig, classified as a liquid-coupled tool, generates shear waves in the pipe wall by the angular transmission of UT pulses through a liquid coupling medium (such as oil in hydrocarbon transport applications). Adjustments on angle of incidence are required to obtain a 45° propagation angle in the pipeline's steel.

The fourth type is the geometry pig (GP) also known as caliper pig. Its functioning consists in measuring the bore of the pipe by mechanical arms or electromechanical devices and identifying so dents, deformations and ovalizations. It is able to detect changes in girth weld size and internal wall corrosion as well as, in some cases, bends in the pipe or buildup of debris on the bottom providing localization, orientation, and depth of each of the mentioned anomaly.

4.2.3. PIPELINE PIGGING

In order to perform pigging operations in a pipeline it has to be equipped with launchers and receivers since insertion and retrieve of the pig shall be done without interrupt the product flow to the costumer so without "opening" the pipeline. The pig is first inserted into the launcher, then the launcher hatch is closed. Valves are operated so that pipeline pressure starts to push the pig out of the launcher and so along the pipe. The run of the pig ends into a receiver which coincides with the end of the segment of pipeline inspected. The receiver, which is similar to the launcher, is equipped with a number of valves set up in a way that the pig will go into the receiver barrel while the product flow will bypass it and go back to the main line without affecting significantly the rate. At this point the pipeline flow continues to pass through the bypass until the operating crew arrive to open the mainline valve A, then close the trap valve B and as last close the kicker/bypass valve C that we can see in Figure 8.

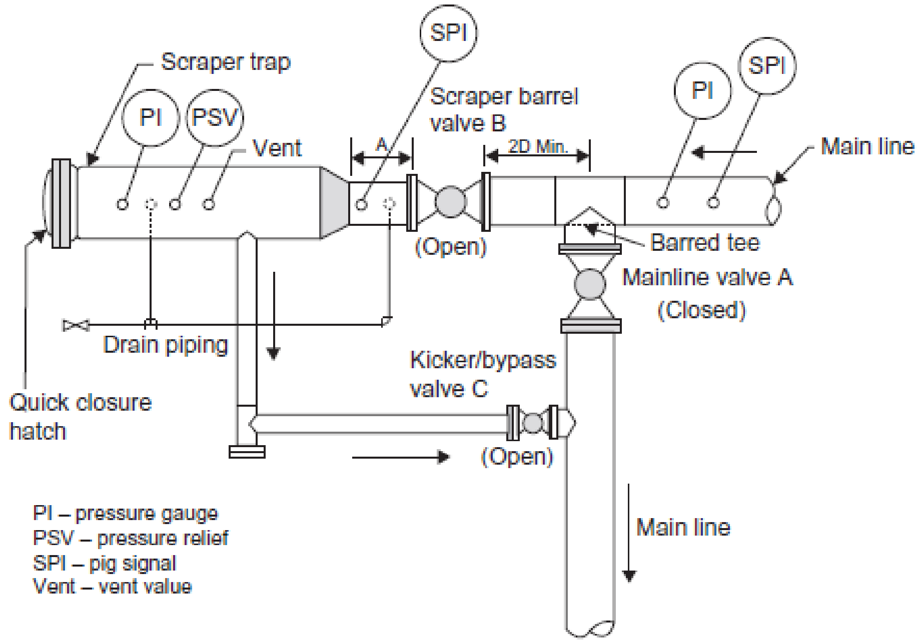


Figure 8. Scheme of a typical piping for pig launcher/receiver station (top view)

In the figure we can also observe some of the vents, drain pipings, scraper trap instrumentation and pressure relief valves required for a launcher/receiver system. Fundamental is the pressure-relief device which must be able to totally relieving pressure in the barrel before the insertion or removal of the pig. In addiction a suitable pressure gauge must be mounted to guarantee to operator that the barrel pressure has been relieved for a safe opening of the hatch.

4.2.4. SMART PIG PROPULSION

Like all the other pigs they travel along the pipe propelled down by differential pressure between the pipeline part preceding the pig and the one succeeding it as shown in Figure 9. Here below:

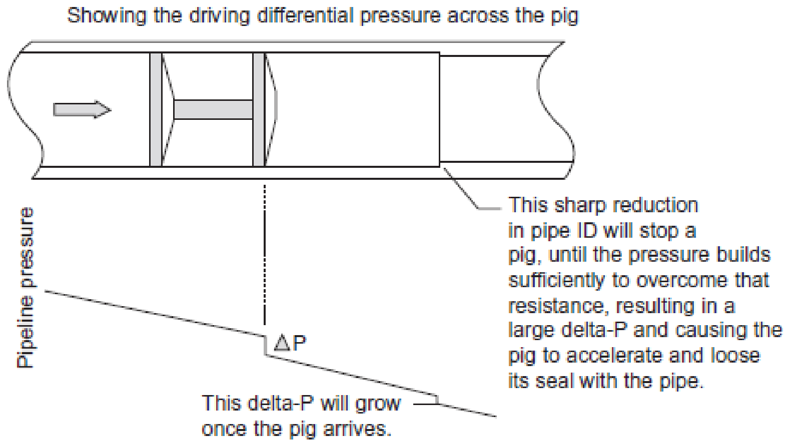


Figure 9. Pig propulsion scheme

Pig movement is only influenced by differential pressure and friction force due to internal pipe wall, furthermore the sealing of the pig against the wall is fundamental for it to work properly. A reduction in pipe diameter or a tight radius bend can modify friction condition and the pig could remain stuck. It will be able to move again just when differential pressure builds up until friction force is overcome. At this point the pig is free to move but it will accelerate as much as to cause the loss of contact, and so the sealing, with the wall making each of pig function ineffective.

4.2.5. PIGGABLE PIPELINES AND PROBLEMS

Any pipeline for hydrocarbon products transport designed and built in the last 30 years or so should be equipped with launchers and receivers suitable for all type of conventional pig since, thanks to their proven benefits on long-time scale and expanding capabilities, their use growth enormously respect to the beginning. Due to number of instrumentation mounted on Smart Pigs, their size is different from conventional pigs. For this reason most of the times the launcher/receiver barrel needs to be modified to accommodate Smart Pigs. Particularly the pipe length between the trap and the barrel have to be increased of a quantity A to support these heavier pig: 16-in.-diameter pipeline requires A to be 13 ft long while 24-in.- diameter pipeline requires a 10 ft long one. Of course once adapted for Smart Pigs the trap station will work fine for conventional pigs as well.

In a piggable pipeline, trap station are typically spaced 50÷70 miles between them. Other features required for a piggable pipeline are: pipe bending which must be designed with a long radius, the use of bared tees at all branch connections in order to avoid pigs to be catched at a pipeline lateral, a full-port design for all mainline valves according with API-6D and pig passing designed check valves.

Anyway several pipeline, especially the most aging, are impossible to be equipped with pigging systems for different reasons: some were designed with a too small diameter to accommodate pigs, short radius bends or with unprotected branch connections which means that pipe tee connection are not equipped with bars needed to keep pigs from being catched and blocking the flow. Further problems are created by mitered elbows, reduced check valves and cases of corrosion leaks which were repaired through the insertion of a screw into the corrosion pit to plug it and then wrapped with a steel band and rubber gaskets.

4.3. *Acoustic Leak Detection Techniques*

4.3.1. LEAKAGE NOISE AND PROPAGATION

A fluid leaking out from a pipe under pressure produces a characteristic noise. Noise's intensity and characteristics depends on several factors such as pipe internal pressure, external pressure and their difference, shape, size and edge of the rupture, pipe material and wall thickness, type and material of joints, type and depth of pipe laying, environmental condition of the soil as well as microphones and amplifiers employed. Particularly the larger is the pressure difference between inside and outside the pipe and the louder will be the noise produced by the leakage. In addiction we can say that between all the mentioned factors, pressure gradient is fundamental for the success of any acoustic prelocalization technique of hydraulic leakage as well as for results assessment. Prior to be captured by instrumentation leakage noise propagates through the fluid, the pipe and even through the soil around. Acoustic techniques take advantage only of fluid and pipe as noise propagation medium. For noise acquisition purpose different points of the system can be used: external to the pipe, such as fittings or the pipe external wall, or internal points. Depending on this choice different propagation phenomena are effective. In the first case sound waves propagating through pipe wall are picked up, whereas in case of internal point use the sound received has been propagated through the fluid. An important consideration is that the sound arriving at the receiver is always different from what the source generated due to the damping effect of the propagation through medium. Particularly the more elastic is the pipe material and the farer is the acquisition point, the more the noise will be weakened.

4.3.2. NOISE LOGGER – PRELOCALIZATION BY ACOUSTIC MONITORING

This technique consists in acoustic monitoring noises present on pipeline or distribution network with the purpose of detecting leakages by their characteristic noises. A number of logger devices are positioned along a buried pipeline through inspection chambers, noise recordings will be memorized and later acquired. Recordings obtained on the same time interval from different logger will be processed and compared and a prelocalization of eventual leakages is performed identifying a restricted area with presence of leakage. Recording, acquisition and detection phases are not instantaneous or automatized , but occurs in different moments.

Noise loggers are typically made by four components: a sensor, a power supply block, electronics, communication device. Sensors are piezoelectric accelerometers specifically designed for this application, highly sensitive in low frequencies field with good performance in every position or orientation and low production cost. Sensor block is typically made in steel or aluminium and equipped with a potent magnet that allows the logger to be firmly secured to the pipe's fitting in any position.

In addition to accelerometers hydrophones are also employed, but they are mainly recommended for plastic pipe or pipes having a particularly large diameter. In these cases hydrophones are secured on faucets, drains or hydrants. Power supply generally consist in a Lithium battery lasting even some years. Depending on the application, battery can be recharged during the data download phase if this requires to pick up loggers, during a stop period in laboratory as for permanent logger or they can be substituted by fully charged battery directly on field.

Electronics host circuits for analog-digital signal conversion, processing and memorization. Modern noise loggers have are equipped with great capacity memory and they are often able to memorize original data in addiction to processed ones. Actually the main limit of noise logger is data transfer: today it is made by radio connection, infra-red IrDA or GSM modules but it happens with a relatively low velocity and for this reason in most of the case only processed data are transferred.

Despite the scarce velocity radio connection allows permanent and semi-permanent relocation of loggers. Once they have been set up and positioned there is no need to retrieve them for the data transfer phase: recordings can be acquired simply by passing inside the area covered by the transmitter with a vehicle equipped with receiver, display and a memory unit which allow to visualize and memorize them. Information sent by the logger consist in the identification number of the device, a noise level and, only in case of advanced model devices, noise level's variance, frequency spectrum and battery's charge level. Recently some models with bidirectional radio connection started to be available on the market. This means, in addition to send data, the logger can be set up or its firmware to be updated directly by the operator from the recording vehicle; this capacity turns out to be very helpful in presence of logger located in critical position such as below a really crowded road.

A good alternative is constituted by GSM modules. In this case patrolling is no more the necessary for data collection: GSM modules are remotely activated each time recordings must be acquired allowing the data center to receive information package from the logger. Due to GSM module's high energy consumption, in order to guarantee a 1÷2 years autonomy they are activated by SMS only for data collection and remains off during the rest of the time.

4.3.2.1. NOISE LOGGER FUNCTIONING

The intensity of the noise caused by a leakage (*leakage noise*) is characterized by the so called fluttering effect which consist in the intensity variability on short time period as a consequence of turbulences created by the leakage itself. Also the *background noise* level recorded at a specific point of the network is characterized by a variability as an effect of water velocity difference, water drawing by users, noises induced by pumps or pressure reducers and, last but not least, vehicles traffic noises and weathering. By comparing these two noise “category” on a long time scale it is possible to observe how variability of leakage noise intensity turns out not to be appreciable but quite constant. Conversely variability of background noise intensity is significantly higher due to, for example, vehicle traffic noise which strongly reduces during night time as we can observe in Figure 10.

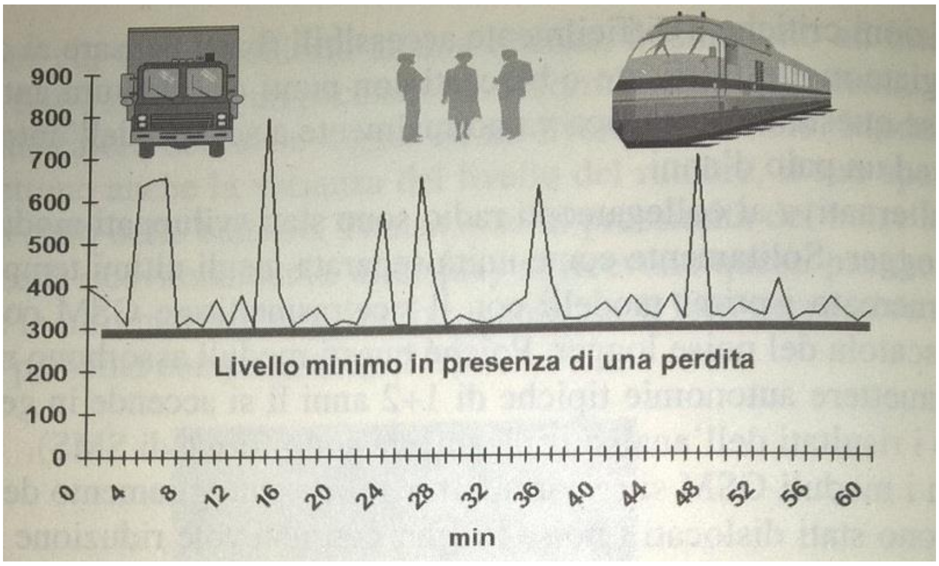


Figure 10. Example of noise signal acquired in presence of a leakage and background noise

Therefore leakage noise will appear as the lower and with quite constant value part of the recording while background noise will be the remaining scattering parts of the recording.

The most effective and widely used representation of noise logger analysis is the chart showing noise intensity's density which looks like a Gauss curve as we can see in Figure 11.

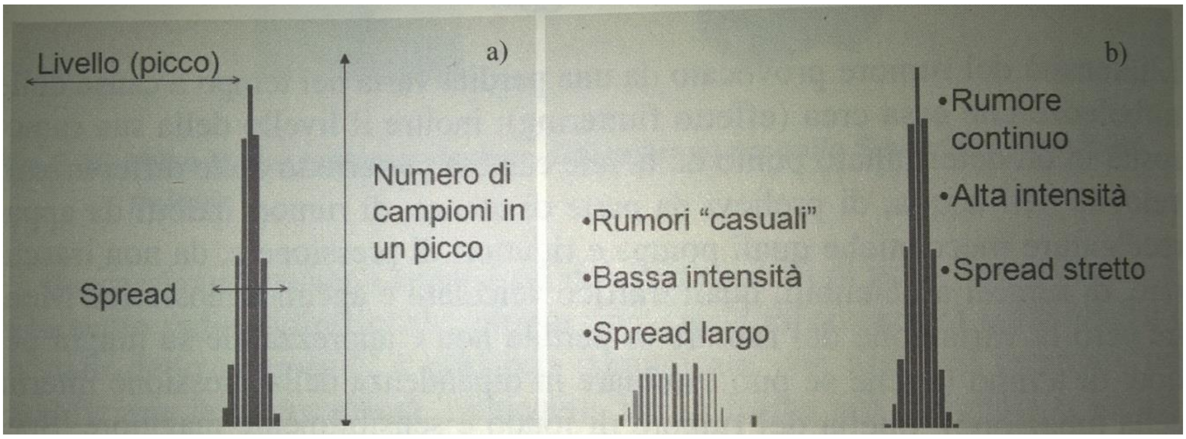


Figure 11. a) graphic representation of noise intensity density; b) typical curves in case of no leakage (left) or in case of leakage (right)

The stronger is leakage noise and its intensity base level, the higher will be its prevalence on background noises and the smaller will be intensity spread; this will generate a narrow and thin curve (Figure 11.a)). In case of lack of, or extremely weak, leakage noise, weak and random background noises will prevail generating an extended and quite flat graph (Figure 11.b)).

4.3.2.2. OPERATIVE PROCEDURE

Employment methodology of noise logger is very variable and customized on characteristics and aim of the analysis to be performed. However three main methodologies can be considered as a starting point as follows.

Continuous Handling: this practice consists in a short permanence and acquisition period, lasting one to two days, followed by recovery and relocation of loggers in new point on the pipe network. This technique is suitable for cases of hard detectable leakages, which require the intervention zone to be circumscribed in a "denser" way, or in case of large portion of a network which have to be systematically inspected, where an higher effectiveness and a large number of logger to be shifted is necessary.

Periodic Handling: this technique is usually employed for district operation, particularly for district start-up phase when abnormal leakage levels are suspected. A number of logger equipped with radio transmitter are installed in several points of the entire network and left in place for a period of few weeks to some months. After a couple of days of monitoring the first acquisition patrolling is performed, data are processed, analyzed and repair operations begins. After the first repairs a new acquisition campaign is run since the noise of larger leakages drowns out smaller ones and the whole procedure is reiterated until the desired stability is achieved; only at that point loggers are recovered.

Permanent Location: it deals with cases of frequently occurring leakage pipes or pipeline in critical areas where the economic damage to citizens would be serious as well as cases where extremely low level of leakage and a reduced detection and prelocalization time are required. In this case particularly accelerometer-type loggers or hydrophone equipped with GSM modules are used .

4.3.2.3. LOGGERS USE

For an effective use of noise logger five phases shall be planned:

- Displacement area assessment
- Positioning on field
- Data acquisition patrolling
- Follow up
- Leakage repair and eventual new patrolling

First phase is extremely important for the final result purpose and must be executed as detailed as possible. Area planimetry and network layout must be carefully examined: diameters, pipe materials, fitting positions, hydrants and gate valves must be known as well as noticeable external noise sources must be taken into account. At this point loggers position are planned and duration and time of sampling are decided as well.

For on field positioning operation the personnel have to set up each logger and install it only after a preliminary inspection of the site which consist in verifying the suitability of the positioning and the correct correspondence with the plan and possible problems which could affect recording phase or recovery operation. In addiction identifications number of both the fitting and the logger must be reported on a positioning form. The logger is attached to the fitting thanks to the strong magnet, paying attention in eliminating any trace of dirt or corrosion deposit which could compromise the hold.

Data acquisition phase changes according to the type on communication medium. In case of logger equipped with GSM module result of recordings automatically reaches operator’s PC without requiring any input to be sent to loggers except of the activation signal. Radio transmitter equipped loggers require instead a patrolling each time recordings have to be acquired. Operator have to cover the road in proximity of logger location passing through the radio transmission range of the logger: once the signal has been detected a spy on the vehicle informs the operator, receipt of data is confirmed and if a probable leakage has been detected a first acoustic indication is given. Less practical but still used is the data transfer by recover of the logger. Especially in the case of Continuous Handling procedure each device is recovered any time the short recording phase ends, once recovered it is laid on recharge and connected for data acquisition. Depending on necessities and plans this operation can be done both on field or in laboratory.

Follow-up phase consists in analyzing data by specific software where they can be visualized or organized respect to different parameters. A logger, usually the one reporting the louder noise, is identified on the planimetry. Then loggers located nearby are checked and basing on the differences in noise intensity or its variance the network’s segment affected by the leakage is identified.

Once the leakage has been detected it must be repaired as soon as possible. Later it’s absolutely necessary to proceed with further investigation on the same area as previously described in the case of Periodic Handling.

4.3.3. ACOUSTIC LEAK CORRELATION SYSTEM

Correlators are instruments designed for an accurate localization of a leakage by using components, such as microphone, amplifiers and filters, which are not so distant from the one used in electroacoustic equipment; what does really change is their use and signal processing. Correlators technologies were improved a lot since their invention: first models were big like a night table equipped with external central unit, microphones and a number of cables while actual devises are totally digital, not bigger of a cigarette pack and equipped for radio transmission of data. However the base principle still remains the same.

4.3.3.1. WORKING PRINCIPLE

As we can observe in Figure 12. a leakage is located in a pipe segment identified by two fittings that are spaced apart of a distance L from each other. A microphone is installed on each of the two fittings for noise recording; the leakage noise propagates along the pipe in both directions reaching first the nearest microphone and the other in a second moment. Based on the difference between the time interval necessary for the leakage noise to reach each of the two microphones the distance of the leakage itself from one of the fittings can be determined. Considering the noise travel velocity v and the unknown distance l between the leakage and the nearest microphone A, we can say that during the time t_1 taken by the noise to reach A it travels the same distance l in the opposite direction. The noise reaches fitting B at time t_2 after a further $L\text{-}2l$ has been travelled. The distance l, which is the goal of the correlation, can be computed with the simple following relation once noise velocity v and time difference Δt have been determined:

$$l = \frac{L - (v \cdot \Delta t)}{2} \quad (3)$$

Particular attention is required in determining propagation velocity as we will better examine in a successive paragraph.

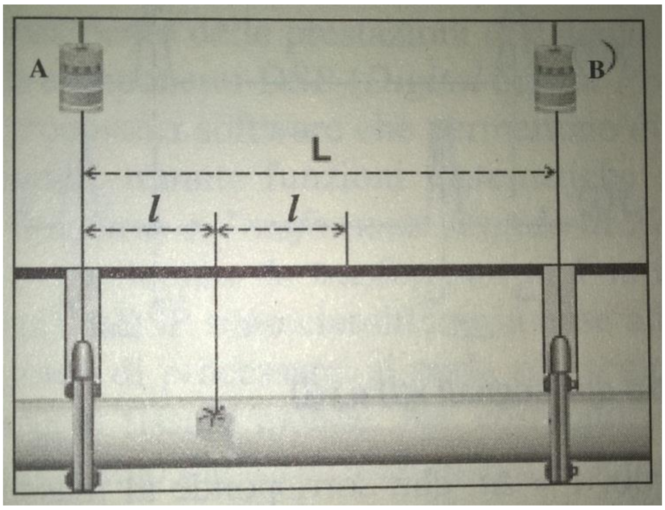


Figure 12. Correlator system schematic

4.3.3.2. CORRELATION

Correlation is employed in Physics to describe similarity of a whatever function to another one. The term "*crosscorrelation*" $R_{xy}(t_i,t_j)$ means the relation or the similitude between two signal $x(t)$ and $y(t)$ changing in time:

$$R_{xy}(t_i,t_j) = \int_{-\infty}^{+\infty} x(t+t_i)\cdot y(t+t_j)dt \tag{4}$$

which corresponds to the *scalar product* of the two signals shifted in time of a quantity t_i and t_j respectively. More in general correlation is the function of the delay τ between the mentioned signals and it is expressed as follow:

$$R_{xy}(\tau) = \int_{-\infty}^{+\infty} x(t)\cdot y(t+\tau)dt \tag{5}$$

At this point, after the delay τ, the two signals are multiplied between them in each point of the time axis with $-\Theta < t < +\Theta$ being Θ observation time and an average is so obtained from the integration of these products. The sequence of *time translation, multiplication and average* is repeated for certain number of values of τ and from these results the *crosscorrelation curve* $R_{xy}(t_i,t_j)$, characterized by having a maximum for $\tau = \Delta t$, is obtained. Signals received by the two microphones can be considered equal, they just differ for a time interval Δt which provides the difference between noise travel times from leakage point to each microphone as we can observe in the following representation:

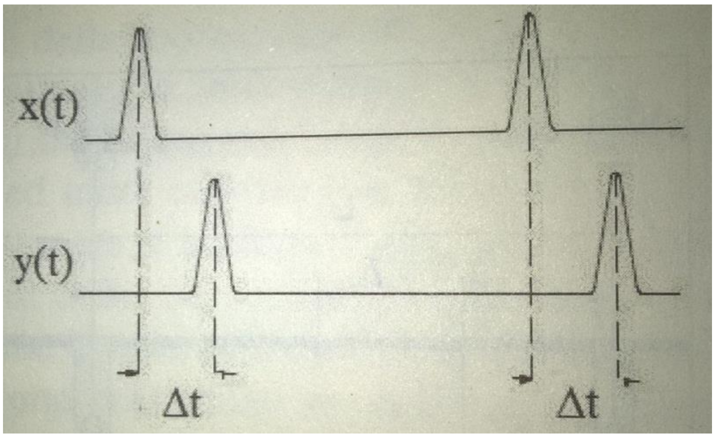


Figure 13. Schematic of the Δt time delay between two signals x(t) and y(t)

In the real practice a finite observation interval $\Theta = t_2 - t_1$ and N sampled signals are considered:

$$R_{xy}(\tau) = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} x(t)\cdot y(t+\tau)dt = \frac{1}{N}\sum_{k=0}^{N} x(k)y\left(k+\tau\frac{N}{\Theta}\right) \tag{6}$$

4.3.3.3. TYPES OF CORRELATION

Leakage noise is normally represented in *time domain* by a function *f*(*t*) but to be used on a modern correlator it needs to be converted into a *digital* representation exactly through a correlation. The fidelity and the accuracy of this representation depends on the numerousness of discretization level so on the number of bit used: the higher is the number of bits, the more precise the digital representation will be.

The simplest type of correlation is *Polarity Correlation* where digitalization occurs with one bit only. Signal is transformed into a rectangular curve which can assume just "1" or "0" value. A more accurate representation can be obtained with the *Amplitude Correlation* which has a larger number of bit available. With 8 bits it has got a resolution equals to $2^8 = 256$ steps but also correlators with a capability till 14 bits appeared on the market. Practical tests showed how for typical localization such a number of bit was more than sufficient since in 70÷80% of them no difference in precision were noticeable.

Amplitude Correlators proves their superiority when noises analyzed are characterized by a majority of low frequencies as in case of plastic pipe or long pipe segment. Another type of correlators are FFT built during 90's: they are software processors capable to analyze and process signals through math function, such as the widely used *FFT- Fast Fourier Transform,* and provided with DSP (*Digital Signal Processor*) with capabilities of 32,24 or 16 bit with fix or mobile comma. With FFT correlator noises described by *f*(*t*) in time domain can be represented also in frequency domain by a function *F*(*v*) of the inverse of time where *v* is the frequency, passing from one domain to another through Fourier transform.

The possibility of a double representation is really useful since operation which turns out to be difficult in one domain are easy if performed on the other one. For example, analyzing a signal in frequency domain allows to clearly individuate frequency ranges belonging to noise disturbance or interference and eliminate them by a properly designed cut-off filtering which operates a selective cut of the selected band on the frequency spectrum. A further spectra coherence analysis highlights frequencies where spectra of each channel are more similar allowing to identify the band where leakage signal exists.

4.3.3.4. CORRELATORS: COMPONENTS AND TYPOLOGIES

A correlators is typically made by the following components:

- Sensors
- Amplifiers/transmitters
- Central unit with receivers

Sensors, which can be accelerometers or hydrophones, convert vibrations or pressure waves generated by the leakage into electric signals. Majority of sensors, called active sensors, are preamplified so once the analog signal is acquired, it is amplified and sent to *Transmitter* by a cable (or even directly digitalized) whose length does not really affect signal's quality thanks to preamplification. Sensors are so linked with *Amplifier/Transmitter* even if many cases of double direct input correlators exist: this allows to work with a single transmitter which receives the signal from the furthest sensor while the one coming from the nearest point is directly acquired.

Different things happen inside the *Transmitter* depending on the signal format: in case of analog signal, it is amplified a second time and a first filtering for disturbance frequencies removal is applied, then the signal can be sent by radio transmission; conversely digital signals can be directly sent but they are often compressed before. Signals are so received by *Radio Receivers* of *Central Unit,* filtered and processed. Digital radio transmission is chosen because it's supposed to be more efficient than a longer analog transmission chain, otherwise the use of digitalization and radio is nonsense (*B. Brunone et al.* 2007, [2]).

However digital radio transmission reveals some problem too, first of all the choice of the best frequency band. To correctly transmit an hypothetical signal having frequencies from 1 Hz, or less, to thousands of Hz, high frequency bands even in the order of magnitude of GHz are required. Such a high frequencies are characterized by relative short ranges due to the attenuating effect of buildings, cars or other types of obstacles which strongly affect the quality of the transmission. Conversely using lower frequency transmission bands would require signal compression through specific algorithms which could cause quality loss of the signal.

The best solution must be found case by case but a common choice its usually the use of special synchronized transmitters able to temporary memorize the signal till radio connection with *Central Unit* is reactivated. Radio receivers are normally inserted into Central Unit even if, since correlators using PC or smartphones as interface started to be used diffusely, it become common to find separated receiver units connected by USB or RS-232 wires as well as Bluetooth or WiFi.

4.3.3.5. OPERATIVE PROCEDURE

Leakage detection by correlators usually counts of four phases as follows:

Preliminary Analysis: this phases preceding any intervention is extremely important since with this detection method leakage noise cannot really be listened so we can only thrust inserted data and results computed. It consists in information collection by studying planimetries particularly focusing on connection between pipes, material variation and path deviation.

Sensors arrangement: since in most frequent cases magnetic fastening accelerometers are employed, cleaning and rust removal from the fitting become fundamental operations to ensure a good contact and a noise transmission. Once the first sensor is positioned the operator have to reach the second fitting covering the exact pipeline path by foot, measuring the distance with a telemetric wheel. Once the second sensor is positioned it is opportune to check if both sensors are on the same pipe.

Sensor set-up: it consists in inserting into the correlator data necessary for the calculation which are the distance between fittings and the noise's propagation velocity even if many correlators require pipe's diameter, thickness and material instead. After a check of filters setting, calculation can be initiated. In case no leakage is showed on display despite there is the certainty of its presence, after having waited a reasonable time a new measurement with different filter setting or different fittings can be run. When the display shows a peak, this indicates the presence of a leakage and its distance from sensors, and it will be the more precise the narrower the peak is. Also the symmetry of the tip position of the peak is indicator of a precise localization of the leakage.

A common case which deserve to be cited is the detection of a loss out of range: if a peak indicating a leakage in proximity of a sensor, a branch or a connection, appears on display it can be caused by a leakage located out of the segment delimited by the two fittings. In this case the leakage noise enters the investigated segment and can lead to mismatching. In this case also, the certainty of the measurement can be verified and corrected by moving the sensor on a farther fitting and repeating the recording.

4.3.3.6. VELOCITY DETERMINATION

The use of the correct value of propagation velocity as input datum to the correlator is fundamental to obtain a precise localization of the leakage, and correlators have different tools available to determine this parameter. Some of them, the simplest, are detailed charts illustrating velocity value for different type of pipe materials and diameters or, in alternative, velocity computation softwares especially useful for uncommon materials or fluids different from fresh water. Despite the easy applicability these two method are completely theoretical and based on the knowledge of the operator about the pipe's characteristic which can be uncertain. More reliable are those method based on the calculation of the exact velocity in the pipe investigated.

For example it is possible to compute noise velocity by knowing the exact position of a noise out of range of the couple of sensors (it can be either a leak noise or an artificial noise). In such a configuration the most noisy point is in correspondence of the sensor which is nearest to the source, while Δt is the time taken by the noise to reach the second sensor. Velocity can be computed simply by dividing the distance between the two fittings by Δt.

A similar but little more complicated way uses the noise within the two sensors range. In this case position of the source must be exactly known and possibly near to a sensor, so Δt must be the highest possible.

However other methods allows to localize leakages even without knowing noise propagation velocity. They are based on repeating correlation after having moved one of the sensors on a different point so that the leakage still remains inside sensor range, or alternatively using a third sensor ("*tri-correlation*") as we can observe on Figure 14.

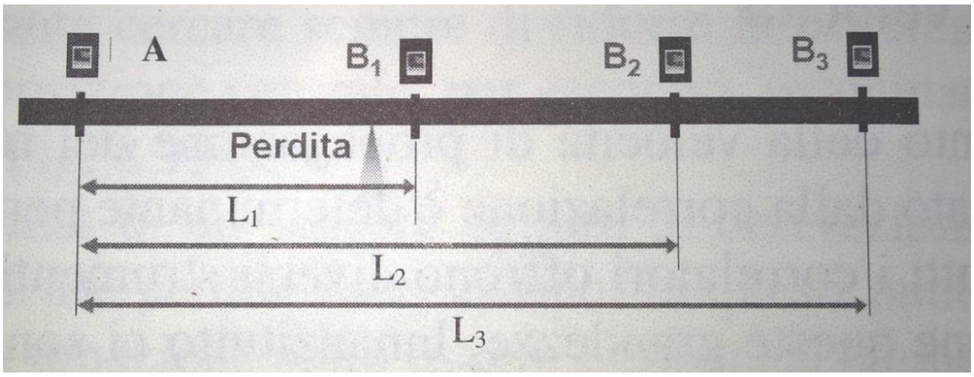


Figure 14. Sensors shift for velocity and leakage location computation by linear regression

By applying linear regression to the equations, the exact distance l from the reference sensor (the one in a constant position) is determined without knowing velocity as follows:

$$l = \frac{L_1 \Delta t_2 - L_2 \Delta t_1}{2(\Delta t_2 - \Delta t_1)} \quad (7)$$

An equally diffused way for velocity determination is a graphic method for linear equation solving. A diagram with *distance* on vertical axis and *time difference* on horizontal axis is used to plot data obtained from each single correlation, then these points are interpolated with a straight line. The distance of the leakage from the reference sensor is obtained by the intersection of straight line with the vertical axis.

In case the investigated pipe section is made by segments of different material all the previous velocity calculation method cannot be applied since they are based on material homogeneity and would provide an averaged value. Assuming to have three different materials, calculation have to be performed by successive steps.

A segment *n* characterized by a length L_n , a diameter D_n, travel time t_n and a noise velocity v_n is considered. After having computed the time difference Δt on the total distance through a cross-correlation function, this is compared with the travel time t_1 belonging to the first material segment: if Δt results to be equal or smaller it means the leakage is located in *segment 1*, conversely if it is bigger it is further compared with the sum t_1+ t_2. At this point if it is $\Delta t \leq t_1 + t_2$ the leakage is in *segment 1* , while if -it is $\Delta t > t_1 + t_2$ this operation must be reiterated until the segment affected and so leakage position are found.

4.3.4. SmartBall™

SmartBall™ is a recent technology developed in the early 2000s by *Pure Technologies* specifically for water transport pipeline inspection, for diameters larger than DN200 (200 mm).

The functioning principle of this system could seems similar to Smart Pigging since it is an ILI (inline leakage inspection) tool but it is not: first because while pigs are designed and customized to perform different tasks, SmartBall™s are designed only for acoustic inspection purposes; secondly because pigs are moved by the upstream-downstream differential pressure and moves staying sealed at the inner pipe wall with their gaskets, SmartBall™ do not.
It is a spherical device which is inserted into the pipeline by a special 4'' valve and it's transported by the water flow, rolling over along the pipe, recording not only acoustic information during its path.

Figure 15. representation of a SmartBall operating inside a water pipeline

This device is made by an outer foam rubber sphere which coats an inner aluminium sphere containing the metering system. Foam rubber is used of course to protect the inner part but mainly to lend the sphere a certain deformability. This allows the SmartBall™ to pass easily through valves, curves, elbows and even height gaps. An accurate design of the size is so necessary but typically a diameter equal or lower to one third the inner pipe's diameter is chosen.

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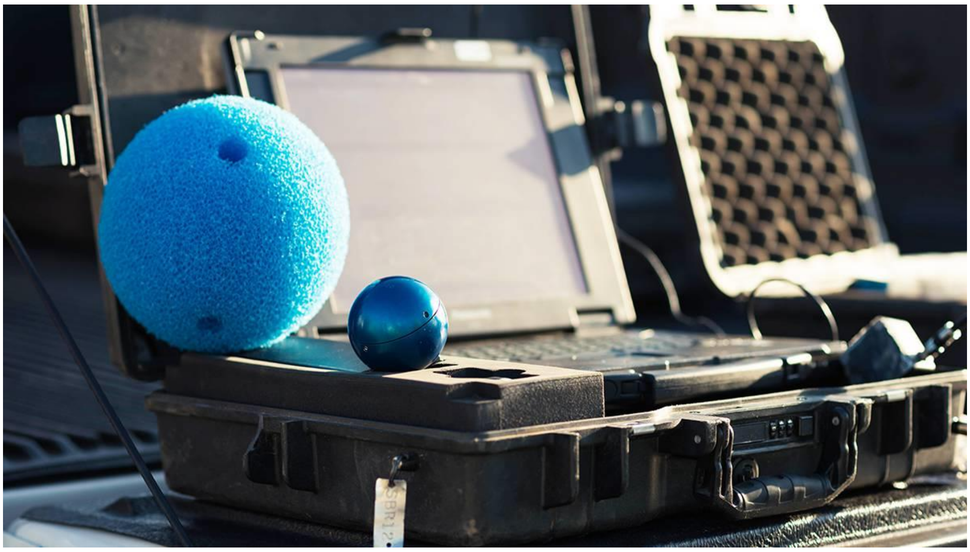

Figure 16. SmartBall outer rubber foam sphere (left) and inner aluminium sphere (right)

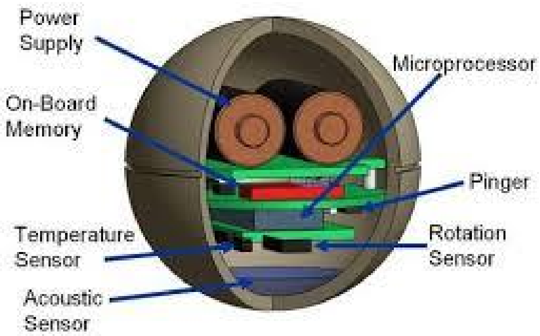

Figure 17. section of the inner aluminium sphere of a SmartBall for water pipelines application

The energy supply is provided by batteries located inside the aluminium shell and lasts more than 15 hours. Furthermore an acoustic sensor, an electronic board with microprocessor and storage, a temperature sensor, a spin sensor and an impulse emitter called "pinger" are installed in the same slot.

Once the SmartBall™ moves along the pipeline it collects and records noises including eventual leakage sounds. One of its distinctive advantages is that, at least in water transport field, it is the only existing ILI system which benefits of the high detection sensibility proper of an acoustic ILI by passing really close to leak-acoustic sources and of its capability to complete really long inspections in a single deployment; all this make the SmartBall™ definitely more effective and substantially more sensible to small leakages compared to traditional acoustic detection methods used in water transport field (i.e. Loggers and Correlators systems).

To retrieve the device a small net tool equipped with a monitoring camera is inserted into the pipeline; data like acoustic profile, travel time and spin number are acquired by connecting the ball to operator laptop through a wire and later processed. It is so possible to display relevant noises in relation to the distance travelled and evaluate possible leakages. A common practice is to perform a second run on the same track, positioning some microphone along the pile to cross-record the passage of the SmartBall™ identified by the characteristic "ping"; this allows to enhance precision in localization.

It proved to be a very effective solution for leakage detection and integrity assessment campaigns as can be demonstrated by the successful application in Netherlands in the period across 2013-2014: an integrity assessment campaign was implemented by the Dutch operator Waternet on two critical portions of its large diameter ($1200\text{-}1500\ \mathrm{mm}$) water transport pipeline covering almost $195\ \mathrm{km}$ of pipeline which were inspected finding three small leakages.

4.3.5. NEW REQUIREMENTS OF PIPELINE SYSTEMS IN THE FIELD OF LEAKAGE DETECTION

Acoustic leak detection methods have been studied since about 1930: they have been employed frequently in different forms for different applications and research field using a wide variety techniques.
As we said above the common starting point of acoustic methods is the fact that when a leakage occurs, the fluid leaking out from the pressurized pipeline generates a noise, an acoustic signal, which propagates through the pipeline in form of acoustic pressure wave. This acoustic signal is so used first of all as an indicator of the presence of the leakage and secondly as information carrier about other features regarding the leakage.

A variety of devices are used to detect and record the leak acoustic signal ranging from acoustic sensors and accelerometers to microphones and dynamic pressure transducers. The hypothetic leakage signal recorded needs then to be quite intensively processed and analyzed to distinguish it from the variety of background noise present on the recording, so to ensure it is truly originated by the occurrence of a leakage, and to retrieve all the information necessary to localize the leakage position and size.

At this point becomes necessary to do some considerations about the different application fields of acoustic methods, the difference between these applications and which necessities motivate a different typology of employment.

When we talk about application fields the intent is to distinguish between water transport field and hydrocarbon products transport field. The substantial feature, which reflects on the differences of the typology and employment of the acoustic methods, lies exactly the nature of the fluid transported: the first fluid is a harmless product, with a relatively low economic monetary and a relatively high availability, thus an eventual leakage of water from a pipeline will not cause any (relatively) important economic damage, environmental damage or injury to people but a disruptions in water supply.

Conversely oil and gas products are dangerous and flammable fluids, highly polluting for the environment and with a considerably higher economic value reason why a leakage, in addiction to cause an obvious consistent economic loss to the operator for the waste of product, represent a serious risk for people safety, for environmental disasters and thus leading to additional economic loss due to heavy penalties.

In simple words ,because of the features just discussed the occurrence of a water leakage can be tolerated more easily, even if needs to be fixed, while an oil or gas leakage needs to be detected and fixed as quick as possible. This introduces a substantial difference in the goal of a detection method used to detect leakage on a water transport system rather than in an oil/gas pipeline as explained below.

In the field of a water transport systems most of the time the real practice which leads to leakage detection consists in two main cases: 1) a leakage is suspected thanks to a water puddle appearing on the ground surface in a visible area or a considerable number of complaints by the users towards the operator, only at that point a leakage detection campaign is implemented; 2) a scheduled leakage detection campaign is periodically actuated to monitor a portion only of the system, whether in case is thought the system is could requires some intervention because of obsolescence, or in case the pipeline was just constructed and may requires a trial stage phase. All this means that the eventual occurrence of a water leakage could not be such a dramatic concern and there may not be an immediate necessity to spot and fix it.

In the oil and gas field the situation is completely different: because of the danger discussed above the goal of a leakage detection system in this field is, at least ideally, to detect and warning the leakage exactly when it occurs, reason why what is needed is a *real-time detection system*.

4.3.5.1. HINTS ON CLASSIC ACOUSTIC METHODS

Between the existing acoustic methods Loggers and Correlators are not suitable for the oil and gas field because of some clear applicative limits as follows.
In case of Loggers their limits are given as first by their reduced action range which would requires a huge array of logger to cover the length of an average sized pipeline, leaving to unacceptable costs; secondly, since the task of a logger consist only in recording the acoustic signal, times (and costs) to acquire, process, analyze the signal to identify the leakage noise would be such long to make everything ineffective.

In case of Correlators the situation is a little better but not enough: as explained in the previous paragraph concerning Correlators this system can detect a leakage in case this last lies in between(or nearby) the couple of hydrophones set on two listening points on pipeline, once the current pipeline segment has been assessed the couple of hydrophones, and the rest of instrumentation necessary, can be shifted to test the following section. We can easily realize as the limiting factor of this method lies in the fact that on only a portion of the pipeline can be tested each time, leading to long detection time. To be more precise, even if hydrophones in some can be spaced till 3 km and a multiple correlator systems could operate simultaneously, this would not be a feasible way to cover long-range pipelines.

Numerous other acoustic methods were developed during years, but in general all of them were based on the use of one between the types of sensor listed above to record the signal propagating along the pipeline or along the fluid. Also from the procedural point of view the various methods are based on the sequence which, starting from the acoustic recording by the sensor, counts in general of signal processing and analysis.
To the purpose of meeting hydrocarbon transport field necessities of a real-time leak detection acoustic detection systems designed to operate in a continuous monitoring mode were implemented thus allowing the detection system to be automated.

Regarding the remarkable issues of the multitude of background noises masking the leakage noise, experimental studies with encouraging results were made about the use of frequency spectrum analysis of the signal which improves the capacity to distinguish the target signal band also thanks to the possibility of applying selective filtering.

As already mentioned the financial downside is the high cost of installing numerous sensors which definitely make this method poorly inviting.
In addition, despite studies and improvements, acoustic leak detection methods remained poorly suitable to the purpose of an effective real-time detection because of their relatively slow response times, low leakage sensitivity, weak accuracy in location and a quite high false-alarm rate thus having a restricted development during years.

4.3.5.2. AN INNOVATIVE APPROACH TO LEAK-ACOUSTICS - STUDY ON LEAK-ACOUSTIC GENERATION MECHANISM FOR NATURAL GAS PIPELINES

Past studies on acoustic leakage detection methods have focused their efforts on the propagation and signal processing of sound waves (also defined as acoustic pressure) leading to the applicative results discussed above with their known limits. However, none of the past studies has bothered to investigate the leak-acoustics generation mechanism which is clearly a key point influencing leak-acoustic characteristics and signal recognition as well as the comprehension of the phenomenon itself.

One of the first and few studies which has been concerned with facing the study of the problem with an approach of this kind was a work conducted in 2012 by *Cuiwei Liu et al*.[4], proposed here below.

In the study in question they start by taking few steps backward, going to what is before propagation and processing, i.e. investigating the theory behind the generation mechanism and the sonic sources of the acoustic pressure signal.

In addition, another brilliant intuition characterizing this approach consists in the idea according to which the “signal” that have to be considered is the pressure perturbation, which is an acoustic pressure drop recordable by a dynamic pressure sensor, conversely to the principle used by traditional acoustic method consisting more simply in the measure of the acoustic pressure.

4.3.5.3. THEORETICAL ANALYSIS

In the case analyzed, i.e. that of the leakage phenomenon occurring in a gas pipeline, the leak-acoustic generation mechanism is based on the *aero-acoustic theory* according to which the origins of leak-acoustics are to be found on fluid-solid interactions and fluid-fluid interactions. By realizing that compelling solutions may be studied within the fluid mechanics field they investigated some of its laws starting from *Lighthill theory,* Equation (16), up to identify the so called *Ffowcs Williams & Hawakings* equation (abbreviated as *FW-H eq.*) used in 1969 as a method to solve acoustic problem generated by objects motion within a fluid.

$$\frac{\partial^2 \rho'}{\partial t^2} - a_0^2 \nabla^2 \rho' = \frac{\partial}{\partial t}\left[\rho_0 u_i \frac{\partial f}{\partial x_i}\delta(f)\right] - \frac{\partial}{\partial x_i}\left[\left(p'\delta_{ij}\right)\frac{\partial f}{\partial x_i}\delta(f)\right] + \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \tag{8}$$

Nomenclature			
a_0	Velocity of sound outsid the flow, m/s	Δt	The time interval between upstream and downstream sensors received, s
a_1	Propagation velocity of acoustic wave in the section of pipeline (0→ x), m/s	T_{ij}	The Lighthill stress tensor
a_2	Propagation velocity of acoustic wave in the section of pipeline (x→ L), m/s	$\overrightarrow{u_i}$	Velocity vector of x, m/s
c_1	The average velocity of the fluid in the section of the pipèeline (0 → x), m/s	x	The distance between the leak point and the upstream acoustic sensor, m
c_2	The average velocity of the fluid in the section of the pipèeline (x → L), m/s	x_i	Value of i-axis In Cartesian Coordinates
f	Generalized function	x_j	Value of j-axis In Cartesian Coordinates
L	The Vistance between upstream and downstream sensors, m	δ_{ij}	Unit tensor
p	Pressure of natural gas, Pa	δ(f)	Dirac δ function
t	Flow time, s	ρ_0	The fluctiations of gas density, kg/m^3
∇	Hamilton operator	ρ'	The undisturbed density of gas or the average density of gas, kg/m^3

Table 2. Nomenclature- study on leak-acoustic generation mechanism for natural gas pipelines

According to the FW-H theory they stated that when a leakage occurs in a gas pipeline three kinds of sonic sources come into play. These three sonic sources are described exactly by the three mathematical terms in the right hand side of Equation (8).

Proceeding from left to right they are respectively: “the monopole sonic source which is caused by surface acceleration or displacement distribution, the dipole sonic source which is caused by surface pressure fluctuations and the quadrupole sonic source which is caused by fluid turbulence” ([4] *Cuiwei et al.* 2012).

Using simpler words the three type of sonic source can be described as follows:

Monopoles
these types of source are the result of the fluid displacement distribution and rigid surface motion generated as a consequence of the rupture of the pipeline wall.

Dipoles
the cause of these sonic source lies in the fluid-solid interaction at the edge of the orifice between the pipeline wall and the compressible gas(or even between gas and valves).

Quadrupole
of all the three sonic sources this is the one generated as consequence of the mentioned fluid-fluid interaction, it is in-fact due to fluid turbulence caused by the gas jetting out of the leak orifice.

4.3.5.4. SIMULATION OF THE LEAK-ACOUSTICS GENERATION MECHANISM

A simulation of the leakage event was performed to study the acoustic pressure perturbation induced by the three mentioned sonic sources. To do so a fluent software was employed and a model was set up considering the following components: main pipe, branch pipe, ball valve, orifice plate and dynamic pressure sensor. More specifically the branch pipe was used to simulate the hydraulic node existing in the pipe flow at the leak point, the orifice plate had the function of simulate the breach on the pipe wall with the possibility of changing size and shape of the hole, the valve was simulating integrity/rupture condition by keeping it closed/open respectively while the sensor was simulated by a so called receiver point.

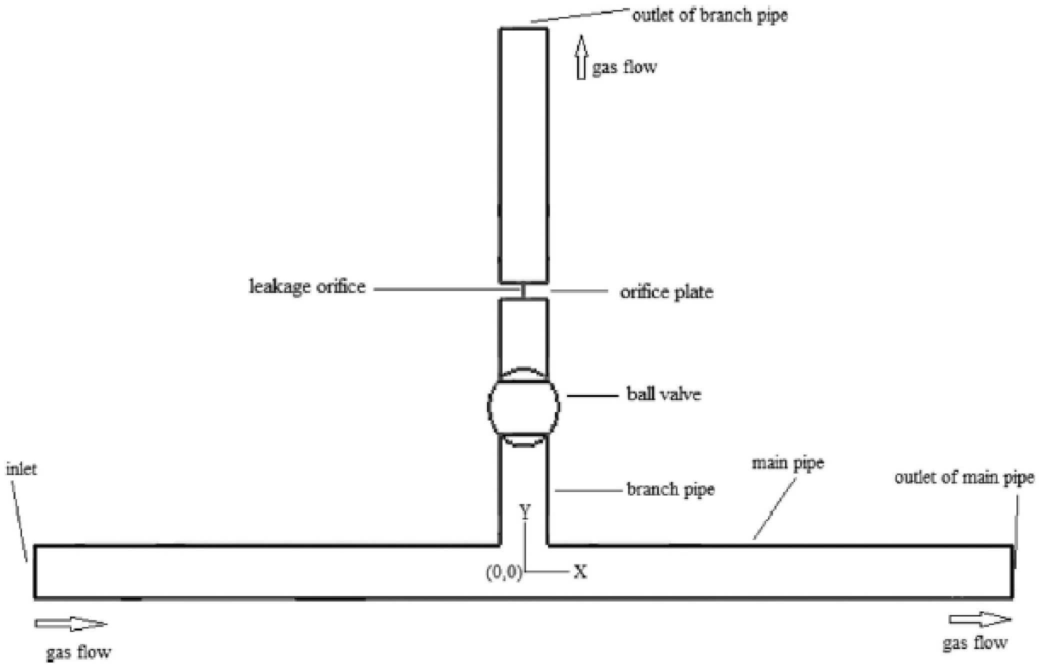

Figure 18. Schematic of the model implemented to simulate a leakage on a gas pipeline

From the point of view of the sonic sources monopoles were generated by pipe wall tearing process simulated with the valve opening. Dipoles were simulated by the interaction of the fluid with the stationary surfaces such as pipe wall, plate and valve while, as you can imagine, quadrupoles were simulated by the gas jetting out. However monopoles sources were ignored because fluid displacement distribution and rigid surface motion resulted quite small.

The acoustic pressure (and not directly pressure perturbation even if these last are the one on which this approach is based on) generated by Dipoles and Quadrupoles were recorded by the receiver point and then superimposed. From the analysis of the superimposed recording they achieved the following conclusions:

a) Quadrupoles are induced at the occurrence of the leakage as a result of eddies crated by the flow of fluid though the branch pipe segment and through the orifice. These eddies are the exact reason of the pressure perturbation appearing on the acoustic pressure recording (the one concerning quadrupole sources) in correspondence of the occurrence of the leakage.

b) The acoustic pressure generated by dipole sonic sources presents a pressure perturbation corresponding to the leakage occurrence which is definitely larger compared to the one belonging to quadrupoles.

c) Pressure perturbations generated at the occurrence of a leakage on a gas pipeline are made of two components: a pressure drop generated by dipole sources and a pressure drop due to quadrupoles.

d) "There exists a pressure perturbation which can be equal to $13\ \mathrm{kPa}$ and the acoustic pressure is always generated no matter before or after the leakage" ([4] *Cuiwei et al*. 2012).

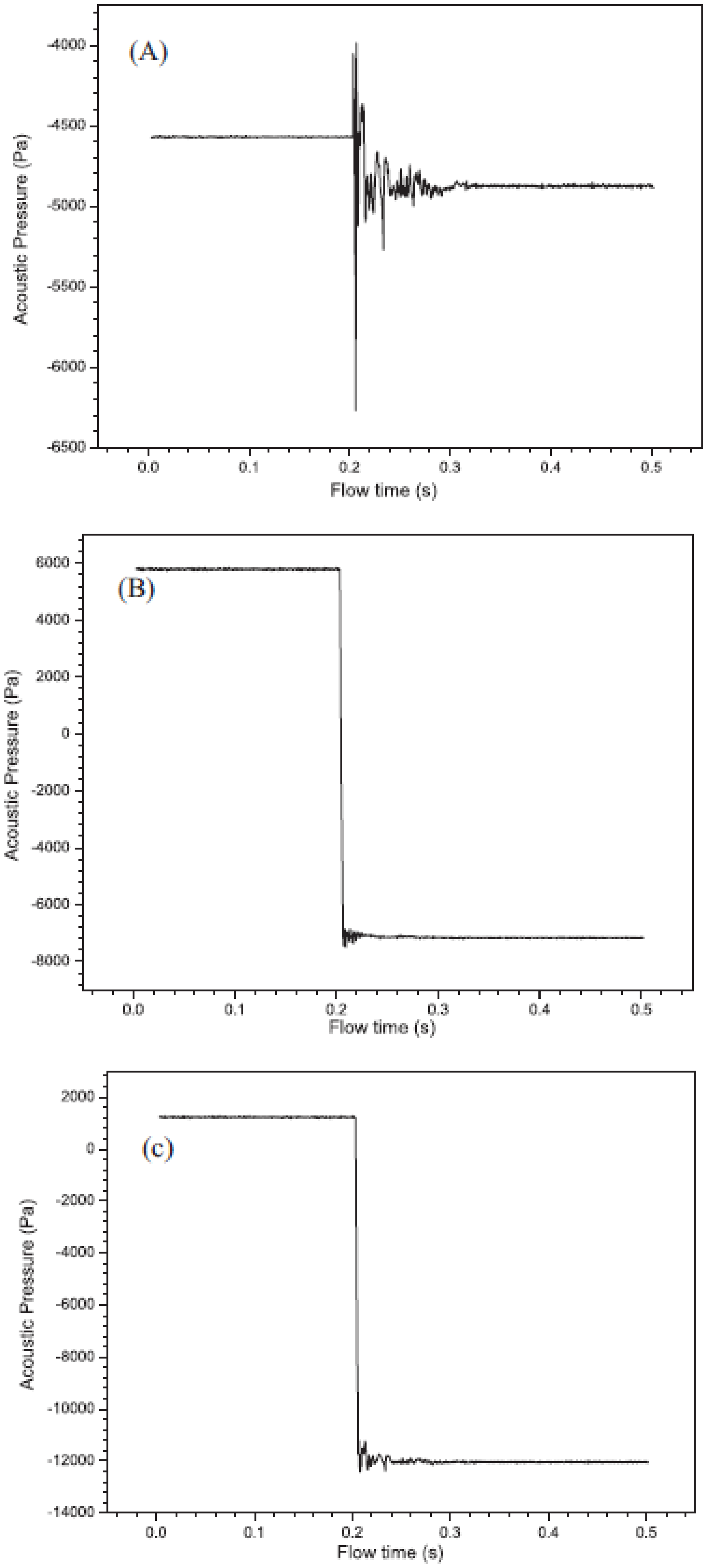

Figure 19. Acoustic pressure analysis by the simulation model. a) Acoustic pressure induced by Quadrupoles; b) Acoustic pressure induced by Dipoles; c) superposition of Quadrupoles and Dipoles induced acoustic pressures

Additional and relevant conclusions were achieved by performing an analysis on the frequency domain: the sound power of leak-acoustics belongs to a $0\text{-}100\ \mathrm{Hz}$ frequency band, meaning that most of leak-acoustic energy lies in low frequencies.

This lead to an extremely important conclusion according to which, since low frequencies are suitable to tens to hundreds of miles transfer, pressure perturbation signal can have a perfect fit for long-range pipeline applications being suitable to be acquired in short time and with a high sensitivity.

4.3.5.5. EXPERIMENTAL ANALYSIS

An experimental analysis was performed by the research team in order to obtain reliable data which allowed them to verify the simulation results. To this purpose a high-pressure pipeline loop was designed and set up in laboratory trying to maintain similarity both with field pipelines and fidelity in replicating simulation conditions. Variable conditions were reproduced in the different acquisition campaigns, by changing operating pressure, orifice diameter, leakage location, etc. The acquisition system used was composed of acoustic sensors, pre-amplifier, signal conditioner, data acquisition card, computer, etc. A dedicated data acquisition software was designed to the purpose, while acoustic pressure acquisition were made by dynamic pressure sensors (model $106B$, $0\text{-}57.3\ \mathrm{kPa}$ measurement range, $43.5\ \mathrm{mV/kPa}$ sensitivity).

4.3.5.6. ANALYSIS OF EXPERIMENTAL DATA AND VALIDATION OF SIMULATION RESULTS

To the purpose of better investigate and comprehend the potentialities of the proposed system, researchers compared results obtained experimentally to the one by the simulation. Particularly the experiment accomplished at $1.3\ \mathrm{MPa}$ with a $0.10\ \mathrm{mm}$ orifice is showed. Interesting consideration can be done starting by the observation of the following picture:

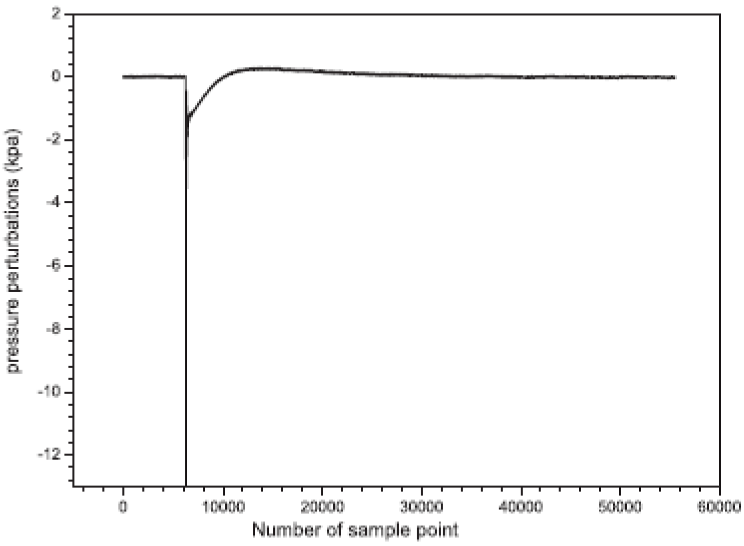

Figure 20. Acoustic pressure perturbation acquired by dynamic pressure sensor during experimental phase

The picture represents the pressure perturbation acquired in a defined time interval by a dynamic pressure sensor. A flat trend indicates a so called stabilization phase where the dynamic pressure remains (or fluctuate close to) 0, which means no pressure perturbations are recorded. Conversely, in correspondence of the leakage occurrence, we can observe an abrupt pressure drop which in this case is equal to $14\ \mathrm{kPa}$.
The delay in the build-up of the trend preceding the second stabilization is not an real concern since is known side effect due to a time gap required by the dynamic pressure sensor before to become able again to returns to balance after a large pressure drop has been acquired.

At this point, in order to compare simulated and experimental results, acoustic pressure data showed in Figure 19.c) are taken in consideration. The chart in question shows acoustic pressure recording obtained by superimposing acoustic pressure signals generated by dipole and quadrupole sonic sources respectively. The reason of the use of the data originated by superimposition is that in reality, therefore in the experiment as well, all the sonic sources take parts to the acoustic pressure generation. However we remind that also monopole sonic source contributed to acoustic pressure in the experiment but, as we said previously, its effect is negligible compared to the other sources.
In order to compare the just mentioned simulation results with those on Figure 20. superimposed acoustic pressure data of Figure 19.c) had to be turned into the deriving pressure perturbation which is showed in the following picture:

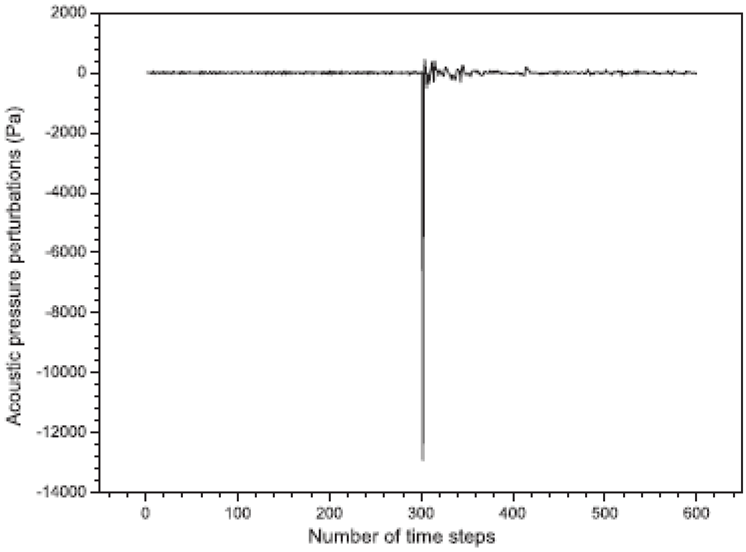

Figure 21. Acoustic pressure perturbation resulting from simulated results

As we can appreciate also simulated results shows an abrupt pressure drop ($13\ \mathrm{kPa}$ exactly)in correspondence of the simulation of the leakage occurrence and the shapes of the two paths coincides very well which is a very encouraging result nevertheless small differences are present.

In addition this good match between pressure perturbations obtained by simulation and the ones obtained from the experiment, which were conducted under similar conditions, suggests that the main part of the pressure perturbations acquired by the dynamic pressure sensor are exactly acoustic pressure perturbations. Traduced in simple words it means that the dynamic pressure sensor turns out to be very efficient as acoustic sensor by acquiring pressure perturbations and not acoustic pressure like traditional applications.

Interesting qualitative results have been obtained by varying test settings parameter either for simulation and experiment and have been summarized here below on Table 3.

	SIMULATION				**EXPERIMENT**
	Dipole pressure perturbation	Quadrupole pressure perturbation	Superimposed pressure perturbation	Influence of Quadrupole	Superimposed pressure perturbation
Leakage orifice **INCREASING**	↑	↓	↑	↑	↑
Operating pressure **INCREASING**	↑	↑	↑	–	↑

Table 3. A summary of the effects of test setting parameters variation

4.3.5.7. APPLICATION OF THE ACOUSTIC DETECTION METHOD – DETECTION OF THE LEAKAGE

To make the presented acoustic method work according to the necessities of a gas pipeline system, so to be able to perform automated real-time detection, it was required to implement the detection system in the following way: once a large pressure perturbation is acquired the system must be able to elaborate if a leakage just occurred or if it is a different issues, and, if yes, to provide a warning. In addiction it's required the system to locate the leakage and estimate the size.

To do so mean values and magnitude of power were chosen as the "characteristics" for leak detection under different conditions. This means the following: characteristics obtained from dynamic pressure sensor acquisition under the condition of no leakage are recorded and between them, the maximum value is identified and used as a threshold.

At this point if dynamic pressure sensors acquire values exceeding the threshold a leakage is detected. Results of the just explained mechanism can be appreciated in the Table 4. here below collecting detections conducted during the experiment.

Operating pressure (MPa)	Leakage orifice (mm)	Distance between leak point and upstream/m	Mean value (kPa)		Magnitude of power (*W.s*)		Leakage or no leakage
			Threshold	Actual value	Threshold	Actual value	
1.50	0.50	–	0.54	0.058	0.014	0.0018	No
		39.8	0.26	4.39	0.2	0.86	Yes
		88.8	0.25	1.60	0.13	0.72	Yes
		149.6	0.33	0.79	0.029	0.21	Yes
	0.45	–	0.29	0.038	0.015	0.0016	No
		39.8	0.29	1.48	0.02	0.021	Yes
		88.8	0.32	1.11	0.021	0.28	Yes
		149.6	0.30	0.44	0.016	0.10	Yes
2.50	0.50	–	0.48	0.11	0.044	0.004	No
		39.8	0.42	4.28	0.12	1.41	Yes
		88.8	0.37	2.16	0.11	1.46	Yes
		149.6	0.43	1.48	0.057	0.78	Yes
	0.45	–	0.57	0.062	0.037	0.0041	No
		39.8	0.45	4.32	0.047	3.46	Yes
		88.8	0.47	1.88	0.071	1.47	Yes
		149.6	0.48	0.89	0.056	0.43	Yes
3.50	0.50	–	0.53	0.074	0.054	0.0064	No
		39.8	0.63	5.36	0.4	7.14	Yes
		88.8	0.51	4.59	0.27	4.43	Yes
		149.6	0.57	1.97	0.055	1.69	Yes
	0.45	–	0.52	0.06	0.039	0.0037	No
		39.8	0.47	5.02	0.041	7.86	Yes
		88.8	0.61	3.78	0.069	1.32	Yes
		149.6	0.44	1.74	0.033	1.25	Yes
4.50	0.50	–	0.63	0.083	0.1	0.0083	No
		39.8	0.70	9.66	0.44	23.25	Yes
		88.8	0.67	6.91	0.16	2.75	Yes
		149.6	0.72	2.24	0.1	0.84	Yes
	0.45	–	0.48	0.064	0.051	0.0056	No
		39.8	0.52	6.51	0.046	3.92	Yes
		88.8	0.48	5.96	0.058	4.11	Yes
		149.6	0.50	2.53	0.058	1.46	Yes

Table 4. Experimental leak detection data under different operating condition

Leak localization is performed from the system by using the following formula:

$$x = \frac{L(a_1 - c_1) - (a_1 - c_1)(a_2 + c_2)\Delta t}{a_1 - c_1 + a_2 + c_2} \tag{9}$$

the terms of which are explained in the Nomenclature chart, while Δt is determined by a cross-correlation algorithm.

In general also leakage location showed encouraging results: the maximum error rate obtained in absolute was 0.399% only as we can see from Table 5.

Operating pressure (MPa)	Leakage orifice (mm)	Actual distance between leak point and upstream/m	Calculated distance between leak point and upstream/m	Time difference (s)	Location errors (%)
1.50	0.50	39.8	39.213	0.345	−0.292
		88.8	88.070	0.065	−0.364
		149.6	150.223	−0.291	0.310
	0.45	39.8	38.998	0.346	−0.399
		88.8	88.602	0.062	−0.099
		149.6	150.273	−0.291	0.335
2.50	0.50	39.8	39.206	0.343	−0.296
		88.8	88.202	0.064	−0.298
		149.6	150.203	−0.289	0.300
	0.45	39.8	39.548	0.341	−0.125
		88.8	88.303	0.063	−0.248
		149.6	150.271	−0.29	0.334
3.50	0.50	39.8	39.463	0.342	−0.168
		88.8	88.232	0.064	−0.283
		149.6	149.979	−0.288	0.189
	0.45	39.8	39.601	0.34	−0.099
		88.8	88.292	0.064	−0.253
		149.6	150.120	−0.286	0.259
4.50	0.50	39.8	39.586	0.340	−0.107
		88.8	88.170	0.065	−0.314
		149.6	149.982	−0.285	0.190
	0.45	39.8	39.745	0.340	−0.027
		88.8	88.250	0.065	−0.274
		149.6	150.061	−0.285	0.230

Table 5. Leakage localization results under different operating condition

4.3.6. GAS PIPELINE LEAK DETECTION BASED ON ACOUSTIC TECHNOLOGY - PIPELINE WALL VIBRATION ANALYSIS

On the same line of thought of the study previously discussed another work conducted in 2012 by *Liang Wei et al*. [15] wanted to investigate on acoustic detection methods in a way that would have allowed them to fully understand the basis of leak acoustics, with the purpose of providing effective solutions to the need of real-time monitor systems for gas pipelines field.
Also in this case the intuition was to have to start right from the basis and to have to investigate phenomena and relations that link and characterize the occurrence of a leakage and the generation of the acoustic signal. The team researched on the leak-acoustic generation mechanism and sonic sources on the basis of the *aero-acoustic theory*, while concerning signal propagation and detection a different consideration was made as follows: the elastic energy release that accompanies the gas jetting out of the pipeline with a high in-out differential pressure induces sound vibrations along the pipeline wall within the acoustic field. Thus, sensing the significant meaning of these pipeline vibrations to the acoustic detection purpose and their link with acoustic pressure they analyzed them with an harmonic analysis technology since, according to them, “the leak pipeline bears broadband harmonic acoustic pressure” ([15] *Liang Wei et al*., 2012).

4.3.6.1. THEORY AND SIMULATION OF GAS LEAKAGE ACOUSTIC FIELD CHARACTERISTICS

4.3.6.2. THE LEAKAGE SOUND PRESSURE EQUATION

The gas flow characterized by high differential pressure which occurs at a gas pipeline leakage can be undoubtedly associated (linked) to what is defined a free turbulent injection situation.
Said that, considering the leak acoustic (here also *jet noise*) with its features and the *aero-acoustic theory* within which it falls it can be stated that the between the three sonic sources *Quadrupoles* are those responsible of the jet noise. In addition we remind how Quadrupoles are exactly caused by fluid turbulences occurring when the gas jets out of the orifice.

At this point relationships between flow characteristics and the acoustic energy caused by the gas leakage were deduced.
It was found how, according to *Lighthill eighth-power velocity theory* the total acoustic power W is linked to gas flow velocity by a proportionality relation which sees flow velocity elevated to the eighth-power as here below:

$$W = \frac{K\mathrm{D}^2\rho U^8}{c^5} \tag{10}$$

where W represents the total sound power of Quadrupole sonic source, D is the orifice diameter, U represents the flow velocity at the leak orifice, ρ is the gas density at the leak hole, c is the local sound velocity and K is the Lighthill constant. In addition c and K are respectively $c = 20.5\sqrt{T}$ and $K = 3 \times 10^{-5}$ where T is the absolute temperature.

Now, considered the quadrupole acoustic source and known that acoustic pressure generated by that last spreads in form of a spherical wave, we express sound power W in function of the acoustic intensity I and the surface of a sphere S in order to explicit the sound pressure term.

$$W = IS \tag{11}$$

$$S = \pi\mathrm{D}^2 \tag{12}$$

The virtual acoustic pressure (or virtual sound pressure) p of a spherical wave in the acoustic field is linked to the sound intensity I by the equation here below:

$$I = \frac{p^2}{\rho c} \tag{13}$$

By putting equations (10), (11), (12), and (13) in a system, the wanted Equation (14) expressing the virtual sound pressure in function of the gas flow velocity is so obtained:

$$p = \sqrt{\frac{K}{\pi} \cdot \frac{\rho U^4}{c^2}} \tag{14}$$

4.3.6.3. THE ANALYSIS OF GAS LEAKAGE ACOUSTIC CHARACTERISTICS

A numerical analysis was conducted to assess and better comprehend the effects of variation of leakage parameters on the characteristics of the acoustic field which derived. Sound pressure p (Pa) and sound pressure level SPL (dB) values were calculated by using different increasing orifice diameters, then the same was done by keeping diameter fix and increasing the operating pressure value $p_0(MPa)$.

D (mm)	2	3	4	5
p (Pa)	34,2023	54,9347	74,0032	93,9877
SPL (dB)	124,6605	128,7763	131,3644	133,4408

p_0 (MPa)	0,4	0,5	0,6	0,7
p (Pa)	74,003	134,29	225,03	327,65
SPL (dB)	131,3644	136,5405	141,0241	144,2876

Table 6. Sound pressure (p) and sound pressure level (SPL) variation under different leakage diameter and operating pressure conditions

As we can appreciate from numerical results listed in the Table 6. both sound pressure p and sound pressure level SPL increases as the orifice diameter increases, the same happens by increasing the running pressure p_0; in addition, looking at acoustic pressure (p) values we can easily understand how “the influence the running pressure p_0 on the acoustic pressure is larger than that of the diameter of the leakage” ([15] *Liang Wei et al.*, 2012).

4.3.6.4. THE ANALYSIS OF PIPELINE WALL VIBRATIONS

As mentioned previously, the acoustic signal (sound wave) generated by quadrupole acoustic sources, in addition to spreading in the form of acoustic pressure through the fluid, forces a vibration along the pipeline wall.

This vibration is not a single frequency vibration but it is characterized by a certain frequency spectrum because also the acoustic signal is a broadband signal, not a single frequency one. Also it was seen how, the acoustic pressure in question, generated by quadrupoles, has not stable values but varies with time in a way which led to suppose, and later confirm, that these vibration was characterized by harmonic path. For this reason, and to the purpose of investigate and calculate the vibration spectrum, an harmonic analysis technology by the ANSYS software was employed to analyze the pipeline vibration.

4.3.6.5. THE VIBRATIONAL MODEL

By using ANSYS software a simulation of a leakage occurring on a gas pipeline was performed. This simulation, where acoustic pressure assumes the form of surface pressure loading vertically along the pipe, allowed to make the graphic representation of sound pressure distribution loading the pipe, as we can observe in the representation here below:

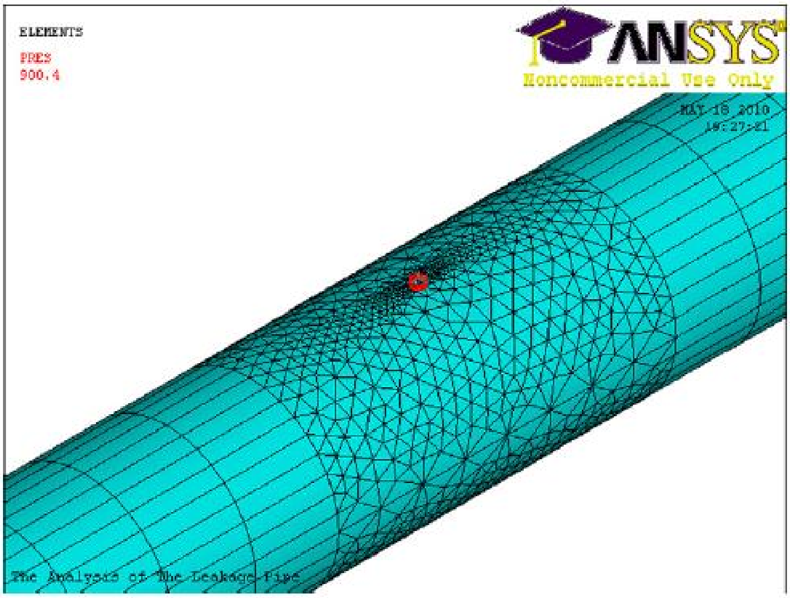

Figure 22. Schematic of sound pressure load distribution on the pipe

Also it was found that "sound frequency distributes high in the middle and low in both side in the far acoustic field" ([15] *Liang Wei et al.*, 2012) and the frequency peak f_p, corresponding the maximum acoustic pressure value, is linked with flow velocity at the leak orifice U and the orifice diameter D by a proportionality relation where U is directly proportional while D is inversely proportional as we can see in the following where β is a coefficient equal to 0.2:

$$f_p = \beta \frac{U}{D} \tag{15}$$

On the basis of what said above it was obtained it was obtained a frequency peak value equal to $f_p = 15.315\ Hz$ which led to an acoustic frequency band which is $0 - 30\ Hz$.

From the investigation of frequency spectrum of different nodes (points) along the pipe length, more or less far respect to the leak position, it was found that in general the vibration maximum amplitude of each node decreases gradually as we go far from the leakage. In addition it became clear as high frequency component of vibration are more affected by damping effect than low ones.

4.3.6.6. FIELD APPLICATION

The proposed detection technique, implemented on the basis of the theoretical and technical insights, and of the results discussed in this study, found a first practical and successful field application on the Donglin gas pipeline belonging to Sinopec.

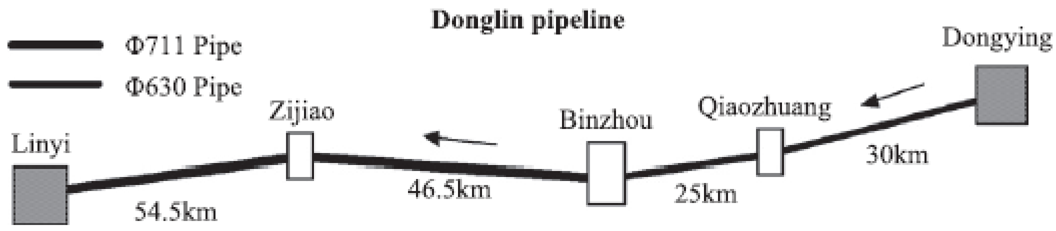

Figure 23. Overview of the entire Donglin pipeline

The pipeline system in question is a 156 km long pipeline divided into four parts the first two of which are characterized by a 711 cm large diameter while the last two have got a diameter equals to 630 cm. In addition it is provided by five stations at the fare ends of each part.

During a regular operative condition of the pipeline the leakage detection system diagnosed its first acoustic pressure anomaly both at the first and at the second station, more precisely at Dongying outlet and at Qiaozhuang inlet, recording an acoustic pressure drop of 6 Pa and 9 Pa respectively.
After checking the leakage signal t pipeline was temporarily shut down to avoid any heavier risk and the leakage last only 20 min.

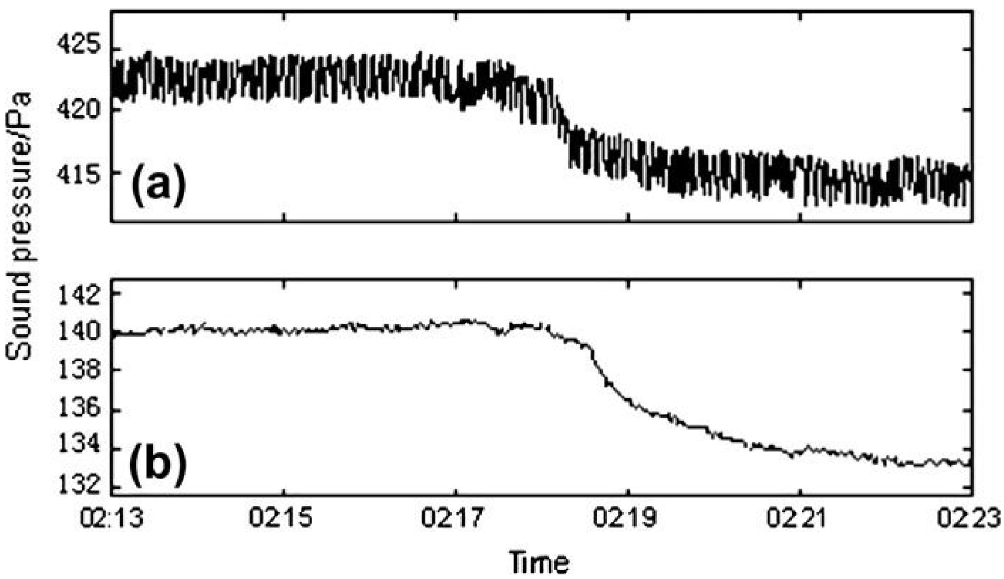

Figure 24. Sound pressure signal acquired at the first leakage event. a) outlet of Dongying station; b) inlet of Qiaozhuang station

After that first detection the system diagnosed additional four leakage occurrences in the next two months the outcomes of which are summarized in the following Table 7.:

Serial number	Leakage time	Positioning error (m)	Leakage quantity (%)	Response time (min)
1	2011-1-23 22:01	+140	0.9	1.5
2	2011-1-27 04:33	+400	1.6	2
3	2011-2-2 20:59	+300	1	2
4	2011-2-3 05:02	+300	1.25	1.5
5	2011-3-12 0:11	+100	1.75	1

Table 7. Pipeline leakage detection results on field, Dongling pipeline

Results obtained during those first three months of monitoring can be definitely said very encouraging. The detection method presented in the study has proved to be up to the scope of diagnosing leakages in a way that suits with pipeline safe operating requirements.
It turns out to have a good sensitivity with a minimum detected leakage equals to 0.9% of the total flow rate while the system response time was on average 1.6 min.

As we can appreciate from Table 7. the leakages were located with a definitely suitable error which on average was $\pm 200\ m$. In addition, even if they are not showed in the table, few cases of wrong detection occurred leading to a false negative rate lower than 5% so in conclusion we can say that the method gave pretty encouraging results.

4.3.7. A SMALL LEAKAGE DETECTION APPROACH FOR OIL PIPELINE USING AN INNER SPHERICAL BALL

For the first time, in the period around 2010, the leakage detection technology based on the use of a tool like the SmartBall arrived at the oil pipeline transport field: a specific SmartBall for oil was developed.

In recent years the potential of acoustic leak detection methods had begun to be re-evaluated and appreciated, nevertheless there were no tools specifically suitable for small and pinhole leakages.

What was certain was that in case you want to detect something, whether is the acquisition of an acoustic signal or the presence of a flaws on the pipe wall like thickness reduction or a principle of crack, the more the “acquisition” point is near to the target (or the acoustic source in the specific case) the higher will be the capacity of spotting something imperceptible.
This is in somehow close to the working principle of Smart Pigs according to which the integrity assessment of the pipeline, therefore the investigation of flaws presence, is performed by launching a device along the pipeline which, passing near to one of those flaws, acquires data about or directly detects their presence.

The intuition of the potential of an acoustic leakage detection system capable to acquire the acoustic signal directly nearby the acoustic source, i.e. the leakage, met the well-established technology of pigging, but the apparently simple idea of using a Smart Pig equipped with an acoustic sensor on board quickly turned out to be ineffective. What makes this application ineffective is the way by which a pig moves along the pipeline: the pig, which is pushed by the pressure difference, lies on a number of wheels touching the pipe wall as well as the set of gaskets responsible of the hydraulic sealing which stay in contact with the pipe wall too. The friction between pipe wall, and these elements produces loud noises which, in addiction to be the reason of the name “Pig”, may make any acoustic recording useless by “covering” leakage noises and leading to an unacceptably low SNR (signal-noise ratio).

The implementation of a SmarBall specifically designed for oil pipelines purpose brilliantly solved this problem: a SmartBall in fact does not scrapes against pipe wall but rolls over it pushed by the oil current.

A SmartBall for oil applications, which we call just SmartBall from now on, consists in a spherical tool which is pretty similar to the one designed for water pipeline applications. It is a multi-sensor inline inspection platform able to acquire a variety of pipeline data since it is equipped with an acoustic sensor, temperature and pressure sensor and an inertial mapping unit comprehending a gyroscope, also it is coated with a polyurethane material to attenuate impacts with pipe wall.

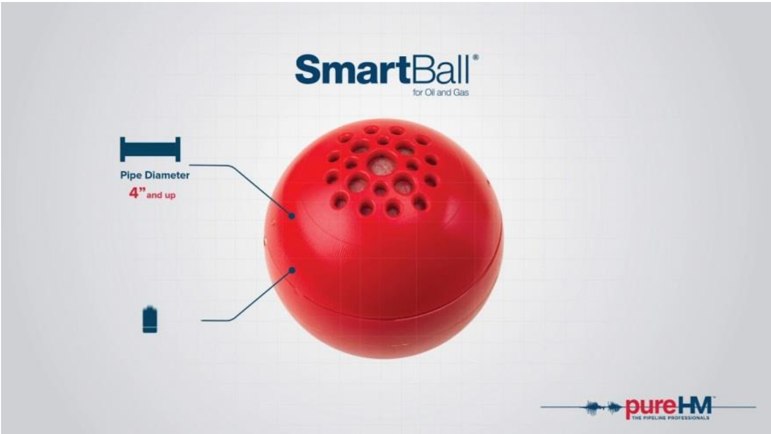

Figure 25. SmartBall® by PureTechnologies for Oil and Gas

This tool can be used for leakage detection programs as well as for regular confirmation of containment surveys since it is able to accurately detect pinhole leakages that for some reasons results undetectable to other ILI tools and fall well-below the detectable threshold of a CPM system: with the acoustic sensor installed on the SmartBall it is possible to detect leakages even as small as $0.11\ \mathrm{L/min}$ that other systems will miss.

As already said this tools operates while the pipeline remains in service; once inserted into the pipeline, typically through an existing valve, it is capable of completing long inspections in a single deployment even lasting $15\ \mathrm{hours}$ then it is removed through another valve by a kind of net.

This last feature particularly make it suitable to be employed also on unpiggable pipelines because, unlike Pigs, it does not need any launcher/receiver station, but mainly it can fits smaller diameter pipelines compared to pigs and pass through tighter elbows. Of course a SmartBall does not aim, and it is not able, to cover all the functions that Pigs do.

Figure 26. Insertion of SmartBall® inside an oil pipeline

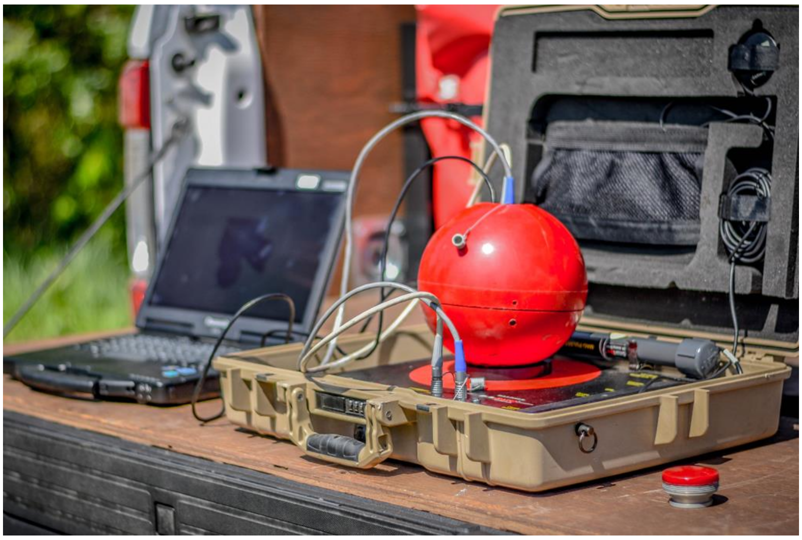

Figure 27. data acquisition on field after the SmartBall® has been retrieved

However, concerning the data acquired, the SmartBall is equipped with an electronic mother board and a memory to store data which are downloaded on the operator’s laptop once the tool is removed from the pipe and later analyzed.

As said previously its detection sensitivity is definitely higher than the other conventional systems since typically it is even 1000 times more sensitive than those systems so its use can successfully become complementary to them.

4.3.7.1. PROPOSAL OF AN ENHANCED SmartBall SYSTEM

A recent study performed and published by *Tianshu Xu et al*. [21] just two years ago in 2017 proposed an enhanced SmartBall based method equipped with an automatic recognition system of the acoustic signature of the leakage. Such a system was obtained by implementing a special small-leakage model which is an hybrid between a computational aero-acoustic (CAA) model and a computational fluid dynamic (CFD) model with the purpose simulate the possible acoustic signature the SmartBall may record passing in the vicinity of a leakage. This small-leak-acoustics models are then coupled with a signature extraction system inspired to formant recognition methods employed in automatic speech recognition.

4.3.7.2. THEORETICAL ANALYSIS AND SIMULATION

Known that in-out pressure difference at the leakage make the fluid leak out in form of a turbulent jet, researchers started by making the consideration according to which turbulence, corresponding to Quadrupole sonic source as we saw in previous paragraphs about acoustic generation mechanisms, is the main responsible of leak-acoustics.
Lighthill equation was individuated as a starting point to investigate the relationship between turbulence and sound generated; in addition the homentropic (entropy= constant) flow condition was assumed leading to a simplified form of *Lighthill equation* as follows:

$$\frac{\partial^2 \rho_a}{\partial^2 t} - {c_0}^2 \frac{\partial^2 \rho_a}{\partial x_i \partial x_j} = \rho_0 \frac{\partial^2 v_i v_j}{\partial x_i \partial x_j} \tag{16}$$

where c_0 is the speed of sound, ρ_a is the acoustic variable.
In this equation, which is nothing else than an inhomogeneous wave equation, the term at the second member represents the aero-dynamic source contribution (i.e. it represents the acoustic source) while the two terms on the left side represents the acoustic propagation. The target is likely to compute the aero-dynamic contribution through the solution provided by an unsteady CFD simulation.

By substituting the acoustic variable with $\rho_a = -i\omega\phi/{c_0}^2$ the finite element form of the weak solution of the *Lighthill equation* above in frequency domain is obtained:

$$-\int_V \frac{\omega^2}{\rho_0 {c_0}^2} \phi\delta\phi \, dV - \int_V \frac{1}{\rho_0} \frac{\partial \phi}{\partial x_i} \frac{\partial(\delta\phi)}{\partial x_i} dV = \int_V \frac{i}{\omega} \frac{\partial(\delta\phi)}{\partial x_i} \frac{\partial v_i v_j}{\partial x_j} dV \tag{17}$$

Since ρ_a was substituted, ϕ became the first acoustic variable, while the aero-dynamic source term on the right became its own volume integral over the source region, which is what we want to elaborate by CFD simulation.

The purpose of CFD simulation consists in passing from fluid parameters such as ρ or v to acoustic results in frequency domain and this is obtained through the following steps:

- Simulation of the unsteady flow (FLUENT software)
- Velocity and density field in the leakage region are obtained at each time step
- CFD variables of the transient model are transformed into acoustic sources
- These lasts are then integrated in the acoustic mesh (ACTRAN ICFD module)
- A FFT is applied on the acoustic sources to pass to frequency domain
- The sound source propagation is computed and maps of the entire sound field are obtained

First a physical model of the pipeline was necessary to the purpose of the above mentioned transient simulations in fluid domain. The model, showed in the following Figure 28., consists into a pipe section equipped with a tiny branch pipe with small diameter to simulate the leakage orifice in the pipe wall. Pipe size and flow parameters as boundary condition are summarized in the Table 8. below.

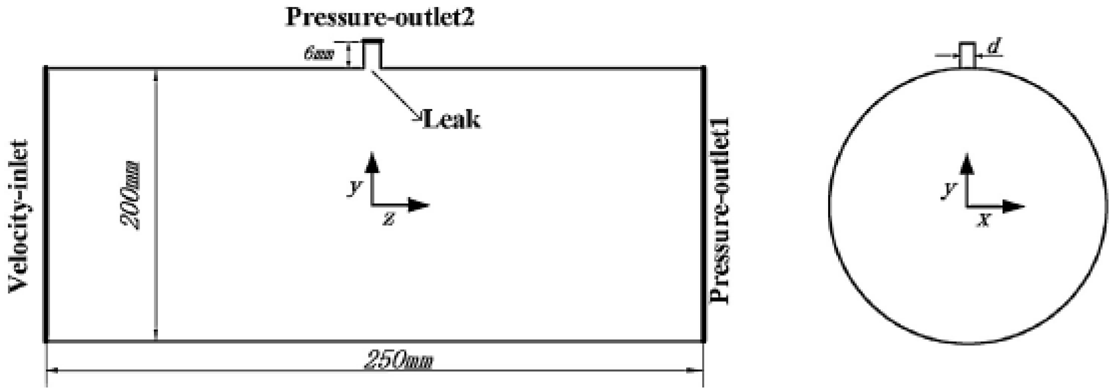

Figure 28. Physical model of the pipe with a leakage on top

pipe diameter D (mm)	pipe length L (mm)	branch heigth h (mm)	branch diameter d (mm)	inlet fluid velocity V (m/s)	pressure at branch outlet $p_{o,2}$(atm)	internal pipe pressure p_1 (MPa)
200	250	6	1	2	1	5

Table 8. Leakage simulation, physical model settings

Starting from this base physical model a 3D mesh model was then realized with particular attention in using a larger number of cells around the hole to ensure an improved resolution locally.

The turbulent behavior of the flow field at the branch pipe, so at the leakage which of course belongs to transient flow regime, was investigated through an eddy simulator software (LES). Pressure and velocity values were coupled through the PISO algorithm while face pressure values from cell pressures were interpolated through the PRESTO !, a discretization method.

Thanks to the steps mentioned so far, three types of contour maps of the branch, therefore of the leakage, are obtained: they are respectively pressure, velocity and kinetic energy distribution representations showing the behavior of the fluid.
What is interesting to observe in these maps are the evidences of the existence of turbulence phenomena since, as far as initially assumed, they are the main responsible of the acoustic sources for leakage. One of these evidences is the area defined by the blue stain situated at the crossing between the main pipe and the branch (pressure contour map, Figure 29.a)): here pressure reaches the most negative value which is $-4\ MPa$ and is the cause of the large turbulent flow inside the branch. The same area corresponds to the red stain (velocity contour map, Figure 29.b)) where the maximum flow velocity equals to $140\ m/s$ is reached.

By observing the kinetic energy distribution (Figure 30.) we can realize how the map area we just talked about is characterized by a kinetic energy 19 times higher than the value of all the points upstream the leakage have ($9500\ m^2/s^2$ vs. $500\ m^2/s^2$) and in general definitely larger than the rest of the branch. This just confirm what *Lighthill Theory* said.

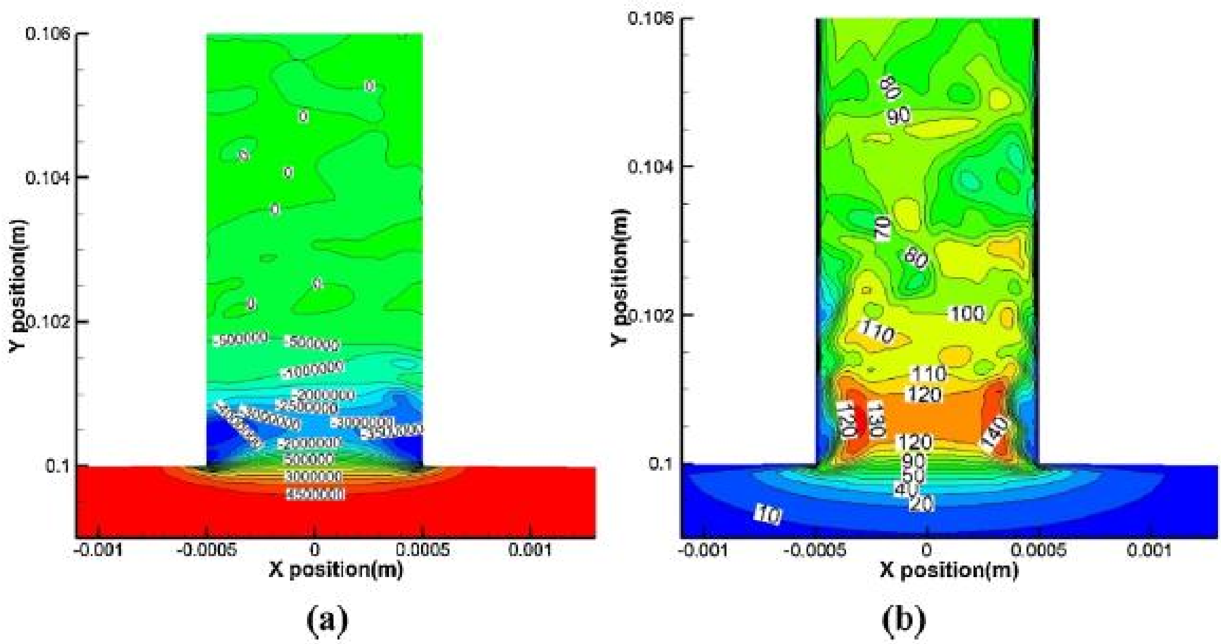

Figure 29. a) Pressure contour map distribution (Pa) at the branch (at the leakage); b)Velocity contour map distribution (m/s)

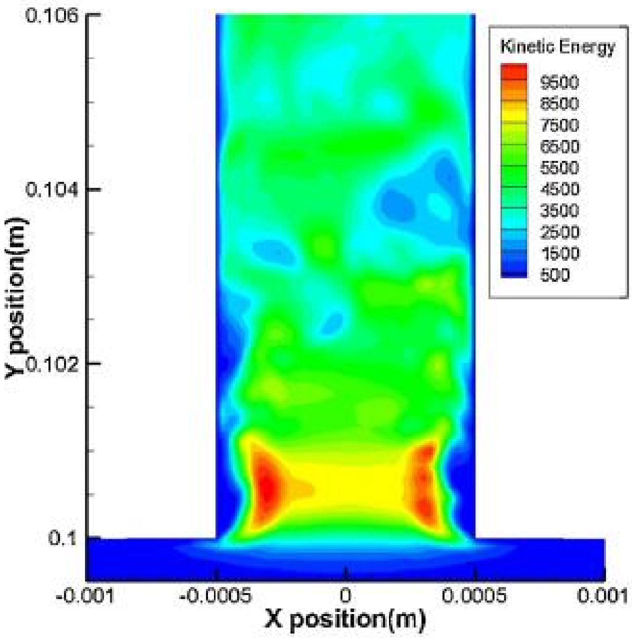

Figure 30. Turbulent kinetic energy contour map (m^2/s^2)

At this point to pass from fluid domain to acoustic domain the CAA had to be performed. The acoustic domain is similar to fluid one showed in Figure 28. with the only difference that the length is $L = 1000\ mm$ also, here the branch represents the source point while the remaining parts of the pipe are the propagation zones.

With the purpose of creating a range of leakage acoustic signatures 16 different leakage cases with different operating conditions were simulated through this model: results and operating parameters can be observed in the chart in Figure 31.

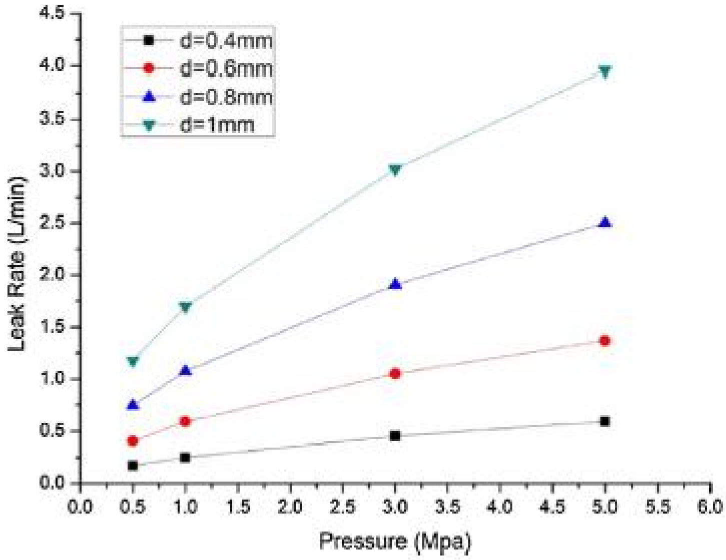

Figure 31. Pipe pressure and leakage rate for different values of orifice diameter

As we can easily see an increase of the pipe operating pressure is followed by an increase in the leakage rate.

Sound pressure spectrum was simulated either at the source point domain and at the propagation domain, precisely at the center point with 0,0,0, coordinates, indicating that the sound source corresponding to the leakage is characterized by a broad frequency band (character frequency 3.1 kHz). Those two acoustic pressure spectra were matched with their corresponding theoretical calculation resulting in a good match. Knowing that the model was reliable other simulations were launched by varying operating pressure value as we can see in Figure 32. as follows:

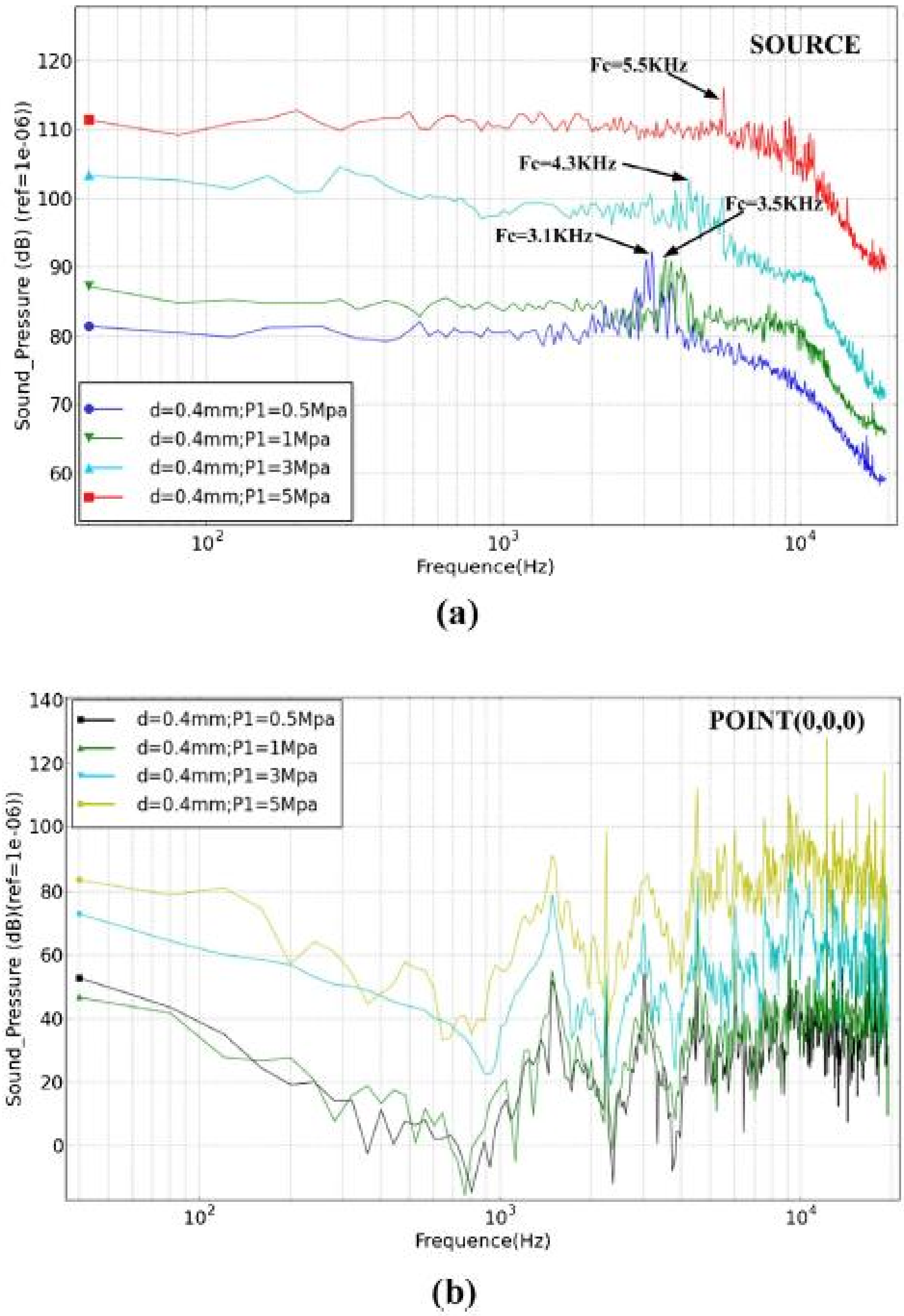

Figure 32. Acoustic pressure spectra obtained by simulation for different values of pipe operating pressure. a) recorded at the sound source; b) recorded at the point 0,0,0

It was found that the character frequency F_c of the whole frequency band is directly proportional to the pipe operating pressure: as we can in Figure 32., especially in a) where sound pressure peaks corresponding to the character frequency are more evident, the value of F_c increases with $p_1$and not only, the whole frequency band increases too.
Another thing to be observed is how all character frequency peaks are situated definitely above 1 kHz.

Values of characteristic frequency F_c and leakage rate V_{leak}were calculated for different leakage diameter, using the same four values of the operating pressure. The relation between the two appeared to be characterized by a constant ratio leading the *Strouhal number equation* $St = f_c L / V_{leak}$ being L the characteristic length of the turbulence.

4.3.7.3. EXPERIMENTAL AND DATA ANALYSIS

The experiment was conducted by using a SmartBall to acquire data about a leakage created in a test-pipe. The SmartBall employed was equipped with a TC4013 hydrophone from TELEDINE RESON characterized by a relatively high sensitivity and a wide frequency range capacity, an accelerometer and a magnetometer to localize the tool within the pipeline. The sphere was designed choosing an optimal ball/pipe ratio of 0.8 and a sampling rate of $40\ Hz$.

The leaking pipe was set-up by using a 200 mm steel pipe long approximately 3 m. One end of the pipe was closed by a bolted flange, conversely the other end was connected to a pump to maintain the required pressure; in addition a sound-absorbing material was used at both the ends to mitigate the occurrence of acoustic reflection which could disturb data acquisition.

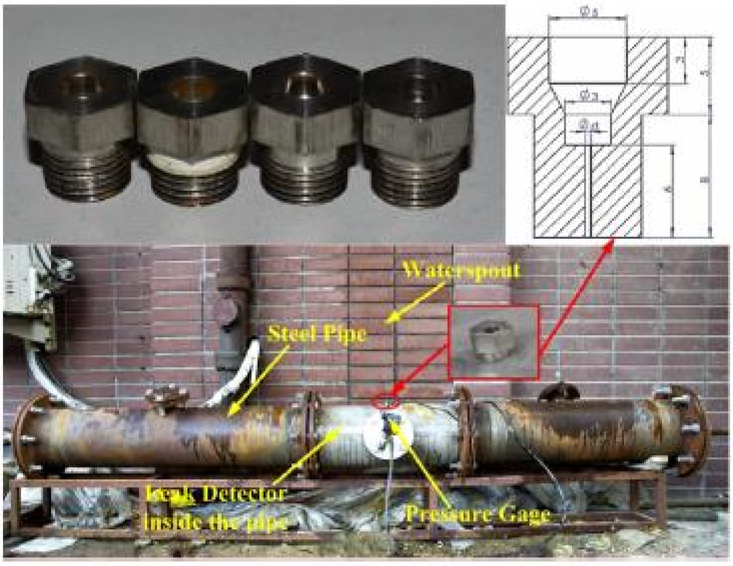

Figure 33. Experimental setting

The leakage was re-created by a hole through the pipe wall which was fitted with a interchangeable valve which allow to reproduce different orifice diameter while the SmartBall was then placed in the vicinity of the leak point to replicate the real case of its passage close to the leakage; in addition water was preferred to oil to perform the test for cost and safety reason.
Since the aim of the test was to confirm simulation results, the same operating conditions were implemented.

The diagram in the following Figure 34. shows the *sound pressure spectrum* obtained from the acquisition characterized by orifice diameter $\mathrm{d} = 0.4\ \mathrm{mm}$ and operating pressure $p_1 = 1\ MPa$ both in case of leakage and no-leakage. The difference between the two spectra is evident: in leakage case it shows two sharp peak respectively at $1.3\ kHz$ and $3.3\ kHz$, both above $1\ kHz$ coherently with what was found out in Figure 32.a) during simulation, while in case of no leakage the sound pressure started from a $40\ \mathrm{dB}$ lower point.

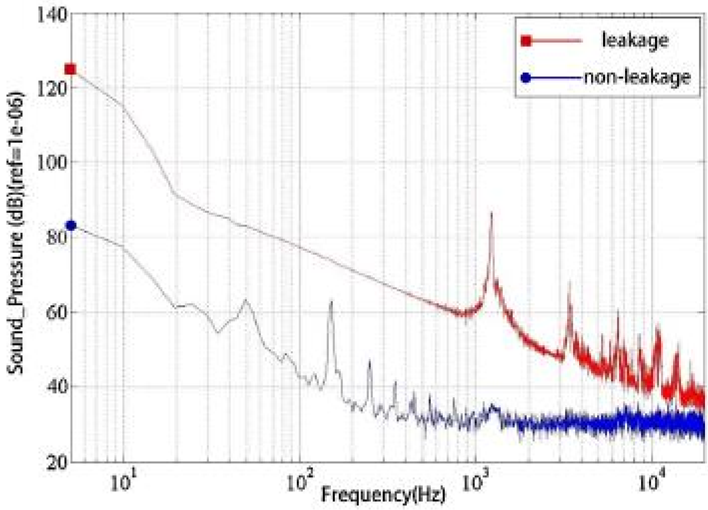

Figure 34. Sound pressure spectrum in case of leakage and no-leakage $\mathbf{d = 1\ mm}$, $\boldsymbol{p_1 = 0.2\ MPa}$

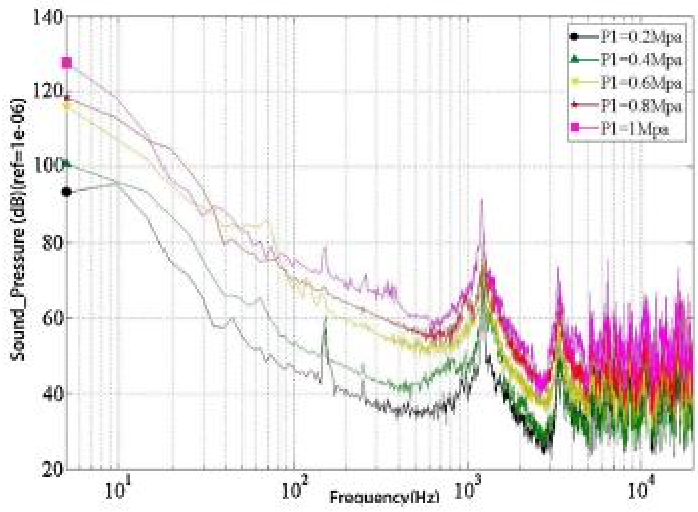

Figure 35. Sound pressure spectra acquired experimentally

Figure 35. shows sound pressure spectra obtained by performing acquisitions with four different and progressively increasing operating pressure values, keeping fix the leakage diameter to the value $\mathrm{d} = 0.4\ \mathrm{mm}$. This exactly replicates what was done during simulation and showed previously in Figure 32. thus allowing an easier comparison.

Equally to what we saw in Figure 34. the presence of the leakage corresponds to two wave peaks, at 1.3 kHz and 3.3 kHz. Moreover, as it has been observed previously in simulations, sound pressure values corresponding to each peak and also the whole frequency band increase with the increase of the operating pressure, confirming the match between simulation and experiment.

Such a path can be interpreted saying that at low frequency band the sound propagates in form of plane waves, the acoustic pressure is characterized by a linear decrease until frequency remains lower than 1 kHz, later a stationary wave rise up, thus the peak appearance at that specific frequency (the same in the four cases) is motivated. In addiction the confusing aspect of the spectrum that follows the peaks is to be attributed to the appearance of dispersion waves which is marked by the cut-off frequency, defined as the value below which only plane waves(and stationary one) exist.

A further test was conducted to verify the hypothesis according to which the signal recorded before and after being passed beyond the leak point should be symmetrical. To this purpose the position of the Smart Ball was shifted a little bit along the pipe axis. The result confirms that once the leakage is passed the signal decays quickly, between seconds 2 and 3 as showed in Figure 36.; this allowed researchers to state that the capable detection distance of the Smart Ball is $\pm$ 1 m.

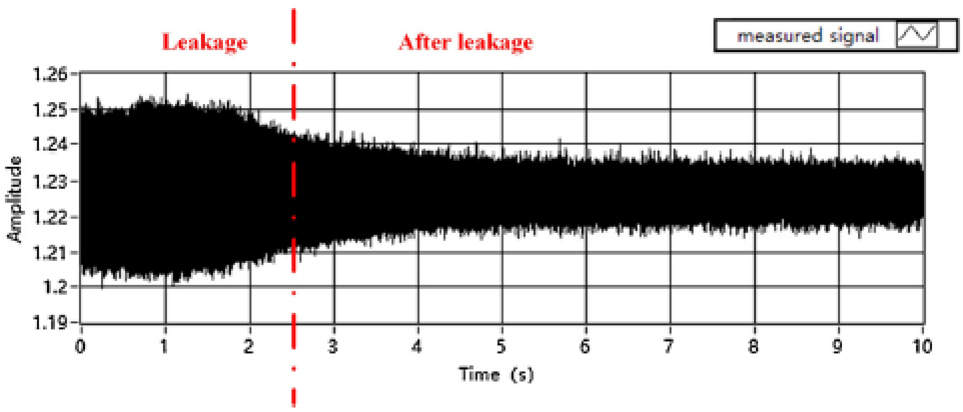

Figure 36. Signal acquired by translating SmartBall along the pipe axis beyond the leak point

Of course such a signals obtained in laboratory experiment benefit of the ideal operating conditions where no background noise is present . The aim of the research is however to reproduce as closely as possible the signal that the SmartBall will acquire when passing close to a leakage in a real acquisition campaign, reason why a field experiment was conducted with the purpose of investigating the effect of one of the background noises that will certainly be present: the noise generated by the collision of the SmartBall against pipe wall during rolling.

The actual rolling signal acquired is showed in Figure 37. here below:

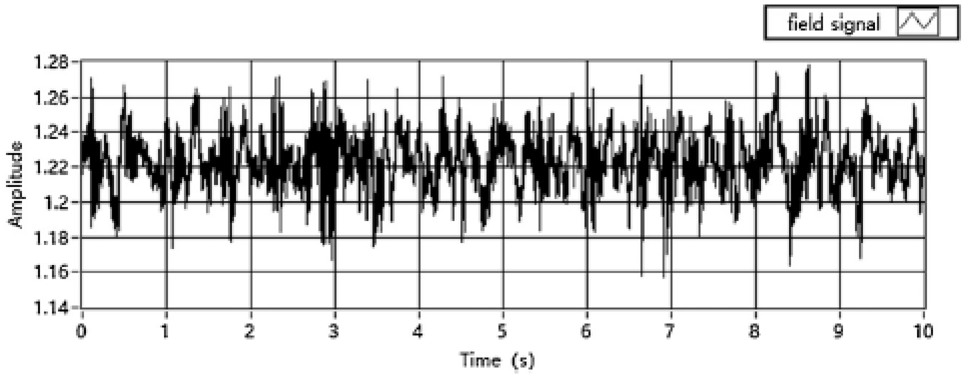

Figure 37. SmartBall -pipewall collision noise acquired on field

By comparing the rolling signal to the leakage signal above Figure 37., particularly if we focus on amplitude, we can realize how the two signal are characterized by the same amplitude ($1.18 \div 1.26$ roughly) which means the leakage signal will be masked by the rolling signal. Thus an automatic signal recognition system able to distinguish signals through frequency features was implemented.

4.3.7.4. AUTOMATIC SIGNAL RECOGNITION

The proposed solution consists in employing the MFCCs scale to describe formants which characterize sound frequency spectra of signals motivated by the fact that Mel-frequency cepstral coefficients and formants in spectrograms are widely employed for automatic speech recognition i.e. ASR.

The identity of a sound frequency spectrum is constituted by specific formants at specific frequencies, which in this case consist in the peaks of the sound pressure spectrum mentioned above.

A characteristic frequency band which is $1 \div 4.3\ kHz$ was identified as the most appropriate for leakage recognition because, as we can verify by observing Figure 35., below $1\ kHz$ the signal is lacking of any distinctive feature (the stationary wave has not emerged yet) while above the cut-off frequency ($4.3\ kHz$ approximately) the signal appears too much confused because of the appearance of dispersion waves.

The recognition system was completed by adding a SVM (i.e. Support Vector Machine) particularly suitable to manage leakage and no-leakage signals: it consist in an supervised learning model associated to an automatic learning algorithm.

This SVM system was trained and tested using of course recordings from experimental acquisitions above but also different noise samples consisting of three types of background noises whether acquired on field or on experimental set which are: Smartball-pipe wall collision, vehicle traffic noise, knocking noise of valves being operated along the pipe. The recognition system proved to be endowed with a brilliant ability in distinguish small leakages from extraneous noises.

4.3.7.5. RESULTS AND DISSUSSIONS

During the experimental phase acquisitions were conducted also on different leakage diameter, keeping the operating pressure fix to $0.8\ MPa$ as showed in the summary Table 9.

leakage orifice diameter d (mm)	internal pipe pressure p_1 (MPa)	leakage rate q (L/min)	leakage % on total flow rate (%)	sample number
0,4	0,8	0,84	0,02	105
0,6	0,8	1,76	0,05	126
0,8	0,8	2,92	0,08	134

Table 9. Experimental leakage detection database

The detection system tested proved to be able to clearly detect even a leakage as small as a rate of $0.84\ L/min$ which, considering the pipe diameter $\mathrm{D} = 200\ \mathrm{mm}$ and the simulation fluid velocity $V = 2\ m/s$, corresponds to 0.022% of the total flow rate.

In addition concerning leakage detection performances, particularly the capacity of the SVM system to distinguish between a no-leakage case and a leakage case, the acquisitions performed during experiment were classified according the following four categories:

- TP, true positive: a leakage exists and it is successfully detected
- FP, false positive: a leakage is detected but it hasn't occurred
- TN, true negative: no leakage occurs and the system doesn't diagnostic any
- FN, false negative: a leakage exists but the system hasn't detected it

Two performance parameters were so defined: *Specificity* i.e. the capability of the system to diagnostic leakages only if they exists, and *Accuracy* i.e. the ability of the system to distinguish a leakage case from a no-leakage case.

According to what just explained calculations were made leading to results which characterizes the system proposed with an *average Accuracy* equal to 93.15% and an *average Specificity* of 94.7%.

4.4. *Hydraulic Leak Detection Methods*

4.4.1. MASS (OR VOLUME) BALANCE METHOD

Since hydrocarbon products have got a considerable economic value there is a strong interest in making sure the amount of fluid injected at the pipeline inlet is equal to the amount arriving at the outlet, both by the shipper of the product and the pipeline operator. For this reason in most of the cases the product is measured both when it is injected into and when is delivered out of the pipeline by some means.

The Volume Balance Method uses the same measurement readings for leak-detection purposes, based on the principle that in case of no leakage the amount of product injected should be equal to the amount delivered.

The metered inlet volume of fluid is compared with the metered outlet one by a volume (or mass) balance equation. In addition, conversely to the case of incompressible fluid, it is necessary to take into account the effect of fluid compressibility: pipeline operating pressures, temperatures and specific gravity are measured and monitored both at inlet and outlet measurement locations. From these, a term called "*line pack*" is so derived. It turns the equation in a straight "net" volumes balance on a prescribed time period as follows:

$$V_L = V_{in} - V_{out} - \Delta V \tag{18}$$

where ΔV = line pack; V_{in} = metered inlet volume; V_{out} = metered outlet volume; V_L = leakage volume. In case of no leakage the value of V_L should be theoretically zero, but of course this is just an ideal case. If it happens that the balance returns a small positive value, then a leakage may have developed or other issues, such as measurement devices malfunctioning, may be occurred. In this case further investigation should be started. Conversely if the balance returns a large V_L value in a relatively short time interval, then a large leakage may have took place. This could require an emergency shot down of the pipeline and, of course, notification to the crew in charge.

The accuracy of this method is mainly influenced by the characteristic accuracy of the flow meters employed and by the calculation adopted to determine the line pack, which can be computed using water hammer equations (*X.-J. Wang et al.* 2001, [13]).
On the other side, the detection time will be mainly influenced by the size of the leak and by the flow regime in the pipeline: large-size leaks and a steady flow regime require a definitely shorter time for detection. For example data collected from Williams Pipeline's program (*X.-J. Wang et al.* 2001, [13]) suggest that the resolution of the detectable leakage has been estimated to be 1% of Q_{MAX} (flow rate) in steady state conditions and 4% of Q_{MAX} in strong unsteady state conditions.

WATER AUDIT

Despite the substantial difference of commercial value, respect to hydrocarbon products, volumes of water transported use to be kept under observation. Also in this field a volume-balance type of method, called Water Audit, is used. In most of the cases the “line pack” term described in the previous Equation (18) is ignored because of water low compressibility. A Water Audit procedure usually start with the division of the distribution network into subdistricts. Ideally a subdistrict is isolated such that we are able to meter inlet and outlet gates for flow measurement and perform the volume balance for a prescribed time period. Since in water distribution networks the flow changes continuously, a water audit requires a period lasting at least 24 hours to be performed (*X.-J. Wang et al.* 2001, [13]). Furthermore working on networks makes the division into subdistrics a hard task since they are highly branched out.

Compared to hydrocarbon transport field sensitivity of Water Audit is definitely lower and is normally about 10% of the total flow rate.

4.4.2. PRESSURE-FLOW DEVIATION METHOD

This model-based method relies on the simple assumption that, in case of no leakage, the calculated pressures and flows should be equal to the measured values.

Pressure and flow measured values are initially taken upstream and downstream the pipeline through the SCADA system (*supervisory control and data acquisition system*) and are later used as boundary condition to set-up the calculation model.

Calculated values can be obtained both by transient or steady state based modelling, even if transient model is widely preferred because of its quicker detection time.

At this point the calculated pressure and flow can be compared with measured values at any location along the pipeline: a deviation between the corresponding values will indicate the presence of a leak. In real cases, even if the pipeline is intact, measured values are quite rarely equal to calculated one. This is due to the limited accuracy degree which affects both measurements and pipeline's model parameters, such as pipe wall diameter, roughness, unsteady friction factor and fluid density. To this purpose a tuning process is required, working on an ideal pipeline with no leaks. It is also necessary to set upper and lower limits on tuning parameters in order to limit the probability for a large leakage to be masked by the tuning process, so to maintain some degree of protection.

This model-based system can be incorporated within the SCADA system so that when the deviation values between the measured and calculated pressure and flows exceed a preset threshold, a leakage alert is generated.

In addition to detection, this method also allows to localize the leakage and to estimate its size, so once the occurrence of a leakage has been identified a further investigation procedure starts. The size of the leakage can be quite easily extrapolated from the flow rate deviation value, while an iterative calculation procedure has to be performed to localize the leakage.
It consists of a series of consecutive simulations: the leak is placed at certain location along the pipeline and a simulation is performed generating pressure and flow values as outcome. These results are then compared to the real measured data. Further simulation with different locations are then run until calculated and measured data fits and the leak has been so localized.

The detection time by using this method, particularly with transient modeling, is normally in the order of minutes and it is influenced by accuracy of measurement, accuracy of modeling and size of the leakage.

An example of application of this method are the site tests performed by Williams Pipe Line. The tests were performed on a 332-mile, 16-inch pipeline and a 190-mile, 12-inch pipeline (*X.-J. Wang et al.* 2001, [13]). For a leak with a rate equal to 5% of the pipeline rate the shortest detection time was 5 minutes. While about localization, given enough time for computing iteration, the error on the location of the leak was about 10 miles for a 5% leak flow rate and 15 miles for a 10% leak flow rate.

A further example is the installation on the Niigata-Sendai gas pipeline in Japan. It was found that: the resolution of leakage detectability was a leak flow of 1.1% of the pipeline flow rate; the average detection time was 4 minutes with a respective error on leak location of 6% of the pipeline length, which was 250km long (*X.-J. Wang et al.* 2001, [13]).

4.4.3. FIELD APPLICATION OF THE PRESSURE/FLOW DIFFERENTIAL METHOD - THE NIIGATA-SENDAI PIPALINE

An interesting demonstration of the employment of leakage detection methods belonging to the pressure/flow differential category is found on the successful industrial application installed in Japan, on the Niigata-Sendai gas pipeline.

The pipeline in question, with its $250\ km$ of length, is one of the longest natural gas pipelines existing in Japan. Its maximum operative capacity corresponds $4500000\ Sm^3/day$ even if, for operative necessities of a $600000\ kW$ power plant supply, the pipeline can be said rarely operated in a steady state flow condition. The pipeline system also comprehends 30 valve stations which are $12\ km$ spaced apart on average.

4.4.3.1. PROPOSED LEAK DETECTION METHOD

The detection method implemented for this pipeline is not a pure *pressure/flow differential method*, it is in fact a sort of hybrid between a *p/f differential* and a *mass(volume) balance* methods. Nevertheless, like in a classic *p/f differential method*, detection of leakages relies also on the mismatching between measured versus model simulated pressure and flow values.

Particularly, about operative parameters measuring, these are metered and recorded in diverse locations through the SCADA system (supervisory control and data acquisition): gas pressure and temperature values are measured at each valve station by pressure transducer and thermometer devices, conversely gas flow rate values are monitored both at the inlet and at the outlet of the pipeline.

To implement the pipeline simulation model the choice fell on a transient state flow model for two principal reasons. The first was dictated by the over mentioned operating necessities which lead the pipeline to operate more in a transient state flow regime than in steady state one in order to comply the power plant requirement. The second reason instead is the research of a quicker (even detailed) system response which can be provided by a transient based simulation model than by a steady state based one since the purpose was to implement a so called *real-time detection method*.

4.4.3.2. PROCESSING STEPS FOR REAL TIME DETECTION

Though that the metering of the over mentioned pipeline flow parameters goes on by itself, we can say leakage detection starts from simulating the pipeline pressure-balance through the just described model.
Although it would be easy to imagine that the predicted pressure data can be obtained simply by launching the transient model, is not that simple since data measured at each valve station are affected by scattering and uncertainty which consequently affects simulation results too as we can better appreciate by what said below. It is exactly on the basis of the pressure and mass-flow data, collected through the SCADA, that two dependent variables are predicted by the transient modeling in fact.

Given this issue affecting data collection a parameter tuning is required so to improve values stability and reliability.
To do so, in the first instance, it is assumed that the potential investigated leakage is simply defined by the mismatch between measured and theoretical mass-balance value at each valve station. The next step consist then in waiting that the system observes a condition of absence of leakage; when this happens tuning can be performed so that pressure balance is reconcilied and potential leakage is minimized at each valve station.

At this the remaining concern is what could be defined as a potential leakage. In other words, assuming that the model developed is able to detect a indefinitely small leakage, at the actual state the amount and the magnitude of uncertainties affecting the evaluation of pressure balance would make the identification of that leakage a nonsense.
This type of problem characterize all mass(volume) balance based methods as well as pressure/flow differential ones, and that is due exactly to the nature of methods themselves, being them techniques which relies on a balance. Therefore the commonly adopted solution to face this issues is to establish a threshold: once a threshold leakage is defined, the potential leakage can be compared with.

As you can easily imagine in case the potential leakage is greater than the threshold it is reported as a (possible) leakage; in addiction, in this application particularly, the leakage occurrence is can be associated to a location laying between two valve station whose threshold have been exceeded as we can observe in the following Figure:

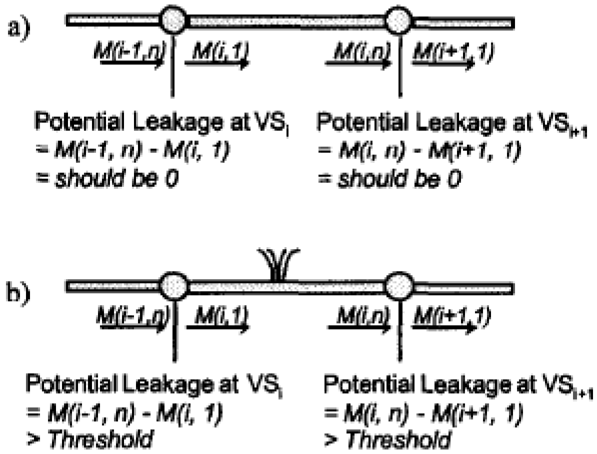

Figure 38. a) Mass balance in case of no leakage; b) Mass balance in case of leakge

4.4.3.3. LEAK DETECTION SYSTEM

About the leak detection system, from the architectural point of view it is composed of six modules as we can observe in the following scheme:

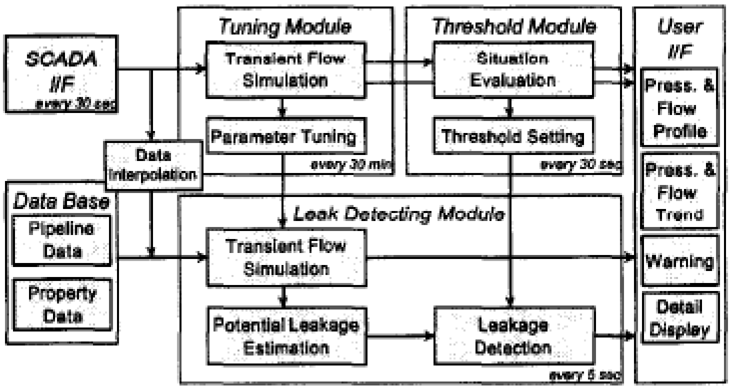

Figure 39. Architecture of the Niigata-Sendai leakage detection system

1:SCADA I/F module

The role of this module consist in the communication with the SCADA system. Particularly the I/F module deals with transferring operational data metered at each valve station from there to the tuning module and to the system's data base by a Ethernet connection. Data packets transferred every 30 s.

2.Tuning module

As explained above tuning deals with data reconciliation. This process goes on with a lower frequency such that a reconciliation is performed 30 min, then tuned parameters are transmitted towards the leak detection module while error in reconciliation is transmitted to the threshold module.

3.Leak detection module

This module is responsible of the simulation of transient flow in the pipeline. Using measured data and tuned parameters it launches a simulation every 5 s. Here a little implementation "problem" requires data to be interpolated since at the inlet data arrives every 30 s while calculation are performed every 5 s as said. Then leakage existence and its location (the couple of valve stations containing it) are obtained by comparing simulated results with the defined threshold.

4. Use I/F module

As last, this user module is the part dedicated to system's users and comprehends a graphical interface where geographical information, received field data readouts, graphs and leakage warnings can be visualized.

Some problems were encountered during the implementation of this detection systems. They were mainly related to flow sensor instrumental error during acquisition both at the inlet and at the outlet of the pipeline and poor resolution of pressure sensors which was directly affecting prediction accuracy.

Additional problems sometimes arose because of the above mentioned pipeline operational regime: as we said product rate use to be changed in order to meet costumer's requirements even leading to daily changes. Particularly in case large demand changes were required, reverse flow phenomena occurred in the downstream of the pipeline causing anomalous system responses such as uncontrolled fluctuations in the detection system and false-alarms.

A solution to this issue was quickly found: employing an on-line learning systems to forecast such abnormal changes the system was made able to perform an automatic tuning of the threshold which was reset to fit the anomaly and distinguish so these false-alarms.

4.4.3.4. LEAK DETECTION PERFORMANCE

The performance of the implemented leak detection system is strongly dependent on parameter tuning exactly because of the way it is designed.
By observing the graphs in Figure 40. which illustrate typical trends of potential leakage at valve stations we can undoubtedly appreciate the compensating effect of tuning on parameters uncertainty.

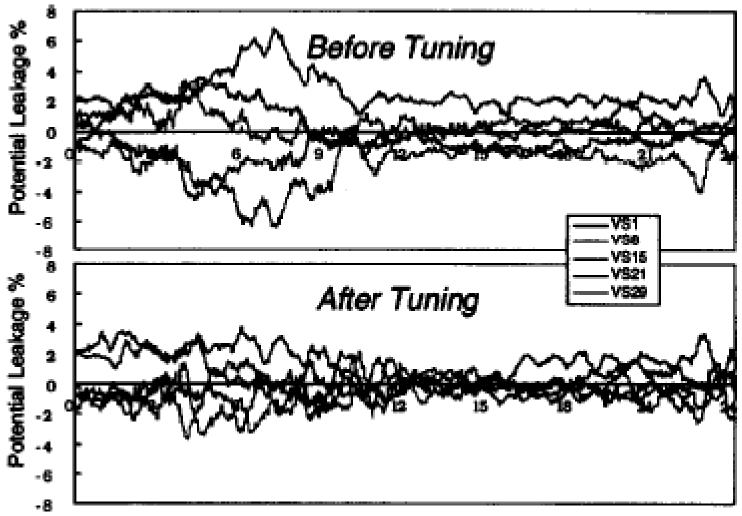

Figure 40. Effect of tuning on parameters acquired

However this leak detection system has led to encouraging results as follow.
A good sensibility in detecting small leakage has been reached: the minimum leakage rate capable to be detected was equal to 1.1% of the total flow rate, corresponding to a 0.9 cm orifice diameter, while the minimum leakage rate that allows to estimate the leakage localization was 1.8% which corresponds to a 1.1 cm orifice.
Since one of the main goal of this system is to capable to automatically detect the leakage occurrence in real-time basis, the rapidity of a correct system response is another fundamental performance factor. The average detection times were 8 min and 4 min, obtained respectively under the maximum pipeline load and the minimum load, while under the greater transient situation the detection time was 4 min.
In addiction the averaged localization error, obtained under the load condition mentioned above was 4%, 20%, and 6% respectively.

4.4.4. REFLECTED WAVE METHOD –WATER HAMMER BASED TEST IN TRANSIENT REGIMES

This method relies on a phenomenon which was always considered dangerous from employees of the hydraulic transport field: the water hammer. This undesired transient flow regime is however a quite common functioning condition in pressurized pipeline systems.

Water hammer is a pressure wave, an impulse, which travels along the pipeline and, as a signal, is able to carry information with him. In pressurized pipeline transient is generated by a rate variation due to manoeuvre of a regulation valve, starting or turning off of an hydraulic machine or, exclusively for investigation purpose, a PPWM device (Portable Pressure Wave Maker).

The theoretical foundation of this method is represented by an important property of pressure waves. When they reach a discontinuity they are reflected and transmitted, totally or partially, depending on the characteristics of the discontinuity.

The distance of the leak from the measuring point, so its location, can be easily calculated once the reflection time (time interval between the generation of the incident signal and the arrival of the reflected wave back to the measuring section) and wave velocity are known. It's necessary for this method to be applied that the initiating time of the transient must be smaller than the reflection time between the leak and measurement location.

The singularity encountered introduces sharp variations on the pressure signal which now contains precious information about system conditions. Based on the subjective (human) capacity in recognizing the effective variations of the signal a diagnosis of the system can be performed. From the analysis and visual interpretation of the differences between the reflected wave and the incident wave it is possible to estimate the size of the leakage.

The method described proved to be extremely adequate to investigate underwater pipelines and long pipelines, where the use of geophones or correlators would be anti-economical, whereas is poorly effective and quite complex for pipe networks application. One of its advantages is the rapidity of execution and the subsequent possibility to be used on a real-time base for monitoring of pipe rupture. It is also convenient in term of cost since the instrumentation required mainly consist in medium precision pressure transducers to be installed at the monitoring section only.

The possibility to perform the measurement from any section (position) of the pipeline allows to bypass all the problems arising in case of inaccessible segments like for undersea pipelines. Furthermore it interferes very modestly with the regular service of the pipeline.

4.4.5. TRANSIENT FREQUENCY METHOD – Pressure Signal Analysis Technique

The visual capacity of discontinuities individuation discussed in the previous paragraph is the foundation mechanism of all the operation aiming to extrapolate information carried from a signal. Some automatic procedures for images identification operates in the same way, so defining discontinuity lines on the images. Therefore it is possible to separate, from the remaining part of the image, all those sharp variations which carry most of the information content and so to manage images in a more effective way.

These automatic procedures can be also applied to one-dimensional signal such as pressure signal: this allows to objectively define discontinuities together with their time and amplitude even when presence of noise disturbs the reading.

Between several techniques one called *Wavelet Analysis* proved to be the best choice to analyze non-steady signals and to define frequency content changing with time. Like other frequency analysis it requires to convert data from time domain to frequency domain. To do so, instead of applying the widely known Fourier transform, the *Wavelet Transform* of a continuous time-domain signal can be defined as follows:

$$WT_\lambda s = \int_{-\infty}^{+\infty} s(t)\psi_\lambda(t-u)dt \tag{19}$$

where *s(t)* is the continuous signal in time domain.

This can be equally defined as the *convolution* of *s(t)* with the "dilatation" of a function *Ψ(x)* called wavelet showed here:

$$\psi_\lambda(t) = \frac{1}{\lambda}\,\psi\left(\frac{1}{\lambda}\right) \tag{20}$$

Differently from the classic Fourier transform where only the frequency term appears, Wavelet Transform is characterized by two terms λ and u. Those parameters, respectively called *scale* and *translation*, allows to explore the frequency content of the signal in time. The *scale* λ have the same purpose of the period in Fourier analysis, while *translation u* allows a localized analysis in time. This is possible thanks to a fundamental feature of wavelet functions which consists in each function being not-equal to itself in the whole time domain and having a finite length.

Here we describe the wavelet model studied by *Mallat and Zhong* (1992) as follows. To do a concise description of this model and how it works it's better to start with a remark: rapid variations, and so discontinuities, of a signal are enhanced if we consider the derivative of that signal. Wavelet transform corresponds exactly with the derivative of the convolution of our signal with a properly chosen function. So rapid variations of the signal are enhanced by the derivative and appear very clearly in form of local maxima and minima in the transform plot.

To better understand the application of this method and how the reading of a Wavelet Analysis looks like we analyze a simple case.

A water transport system is made by an upstream tank, a pipe, a downstream tank, a flow rate regulation valve and a metering section just upstream respect to the valve. Both tanks are atmospheric pressure and the system has got no leakages.

Assuming the valve is instantaneously closed at the instant t_v, a water hammer occurs so a transient is initiated.
A pressure disturbance, so a signal, propagates upstream along the pipeline since at time t_r it reaches the upstream tank and it's totally reflected back. If no other actions are operated on the system, the pressure disturbance moves along the pipeline, alternatively in both directions, being reflected once by the valve and once by the upstream tank.

This behavior is described in Figure 41. where we can see the pressure signal in time domain. Of course the signal is damped at each cycle mainly because of friction effects, but that's not our concern. Our focus is on discontinuities: valve closure and pressure disturbance reflection at the instants t_v and t_r are significant already on the signal trace in time domain.

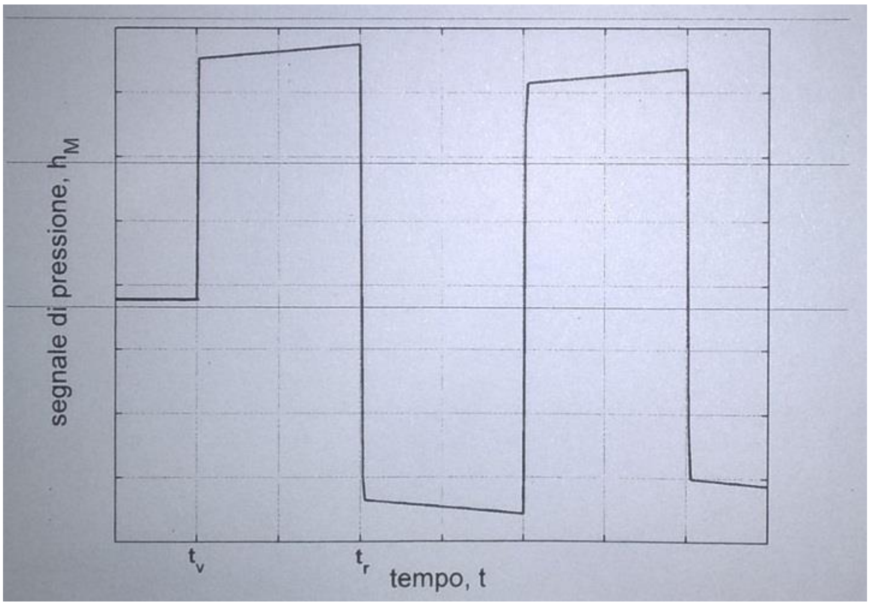

Figure 41. Pressure signal generated by closing totally and instantaneously a valve, intact pipeline case

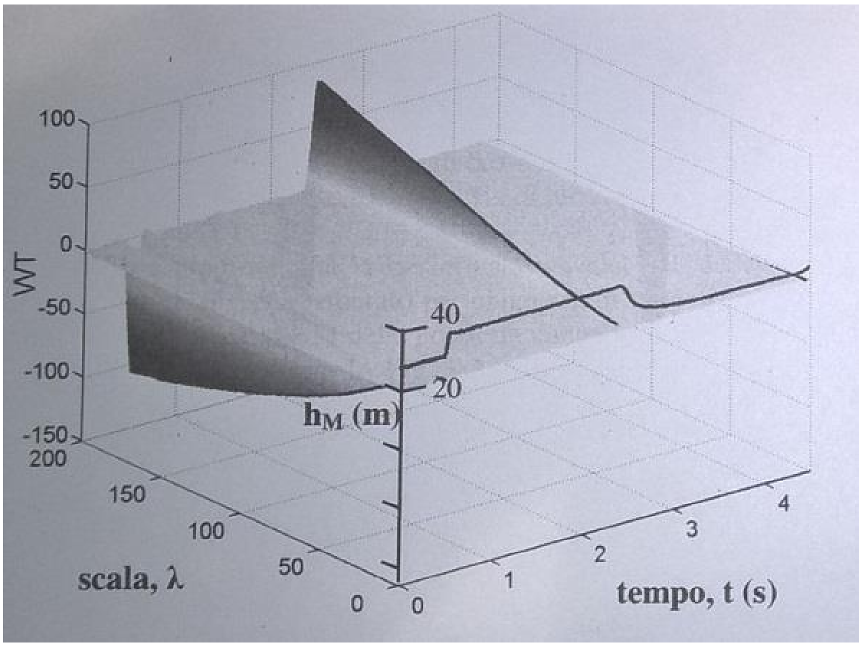

Figure 42. Wavelet transform of a pressure signal acquired in case of leakage

In Figure 42. the Wavelet Transform WT of the signal is showed. Since the transform expresses the frequency content of the signal in time the representation of WT is three-dimentional with *scale λ* and *translation u* on horizontal axes. The crests present in the 2-D diagram in Figure 43. identify local maxima and minima of the transform; they line up in correspondence of discontinuities and form *chains* represented on Figure 42. by two thick black lines.

The base of the method for discontinuities identification, and therefore of the passage of the pressure disturbances trough the metering section, is a reconstruction by scales of chains composed by relative maxima and minima.

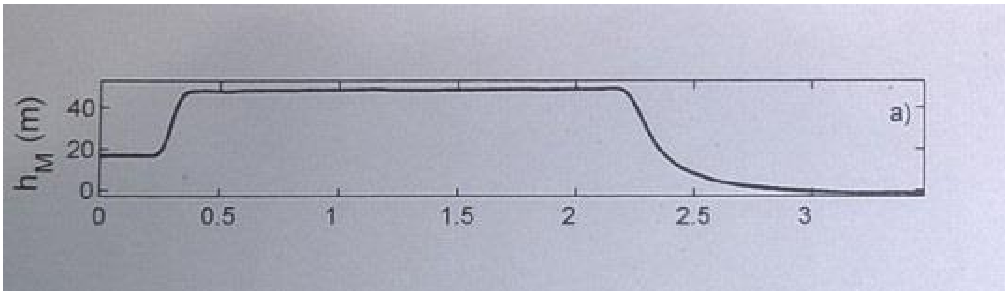

Figure 43. Two-dimentional pressure signal diagram

A first significant advantage is that those lines are not affected by the presence of noise. More precisely, since noise is everywhere discontinuos it leads to the rise of additional local maxima and minima almost all-over the transform; but those noise variations are extremely rapid they does not propagates towards major scales. Therefore only lower scales, which are characterized by lower frequencies, are affected by noise.

This can be better appreciated in Figure 44. which shows the transform on the time-scale plan.

At the highest scale values even a weak sharp variation of the deterministic component of the signal produces a clearly distinguishable maximum. Viceversa, at low scale values where we should have a good precision in localization, discontinuities introduced by noise are quite evident and mask the signal despite their small size.

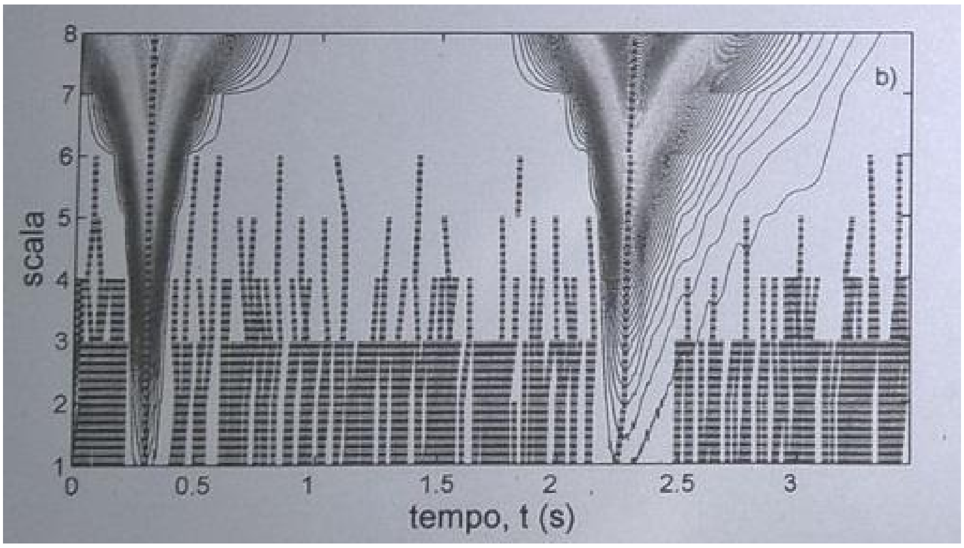

Figure 44. Maxima local moduli chains of the relative wavelet transform before filtering

At this point a compromise between filtering noise and maintain a good precision in discontinuities localization is necessary and Wavelet Analysis at different scales proved to be the best in doing it.

The persistence, after filtering, of local maxima or minima at highest scales at the same time instant reveals the presence of a variation due to a cause different from noise. Conversely a chain of local maxima or minima which stops at first scales it's probably due to noise effect. Applying this criterion the signal was filtered and two chains only propagates till the highest scale coherently with the first two passages of the pressure disturbance from the metering section as we can see in Figure 45.

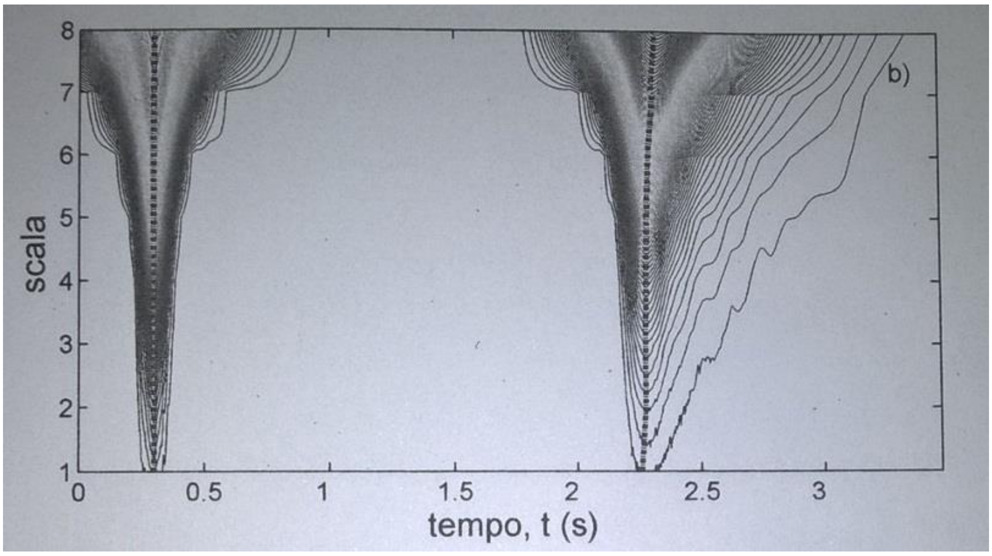

Figure 45. Maxima local moduli chains of the relative wavelet transform before filtering

4.4.6. TRANSIENT DAMPING METHOD

This method relies on the fact that a transient signal propagating along a pipeline experiences a decay caused by the effect of pipe friction and possible leaks encountered along its path. While internal wall friction affects the transient in a “generic” manner, leakages act with a distinctive damping on it. To detect the leakage a comparison on the same pipeline between the leak-affected damping and the damping in case of intact pipeline is so performed. The presence of a discontinuity in the impulse response reveals a leakage. Furthermore the extent of this damping is influenced by the size of the leakage and the operating pressure of the pipeline.

A study, conducted in 2001 by *Wang et al*.[23], analyzed this topic deriving a linear analytical solution to describe the transient in a pipeline with presence of leakages. The analytical solution revealed that the friction-induced damping was an ideal exponential function while the leak-induced damping was looking like an exponential just approximately. Moreover it was discovered how also location of the leakage, transient measurement position and initial shape of the transient influence the extent of the damping .

A detection method was so developed from this analytical solution. Despite this technique does not need accurate determination and modeling of boundary conditions and transient behavior in the pipeline it proved to be a success. Particularly, based on both numerical and laboratory experiments, this method showed the capacity to detect, locate and assess a leakage having a size of 0.2% the cross-sectional area of the pipe.

Transient Damping method is able to provide information about the presence, size and location of a leakage on a pipeline, while its capacity is limited only to detection when applied on a pipe network.

5. Conclusion and discussion

The study pointed out changes in the needs of pipeline transport systems field. Both the greater attention to the already existing plants and the recent increase in the number of gas pipelines under construction with ever increasing lengths have again brought the attention to the importance of methods and strategies that aim to ensure a high efficiency of transport and high safety standards such as methods and strategies for monitoring and verifying the health and integrity of pipelines, in addition to the already well-established prevention strategies.

Particularly, the need for more effective leakage detection systems was found which, by operating in an integrated manner with the pipeline management system, are able to identify even small leakages in real-time, with short response time and good location accuracy thus allowing a prompt intervention to repair and stop the leakage so to avoid potentially disastrous consequences. These systems must be reliable and able to warning the occurrence of a leakage with a low percentage of false detection.

Of all the different detection methods analyzed we wanted to investigate and compare the performances obtained during field applications, focusing on the most widely used methods and the recently proposed innovative methods. In the following Table 10. the main characteristics describing on field performances are summarized:

DETECTION PERFORMANCES		sensitivity (% of the tot. flow rate)	average response time (min)	average location error (m)	false alarm rate
Acoustic	sound pressure perturbation through pipe wall vibration	0,9	1,6	±200	<5%
	SmartBall - automatic recognition	0,02	-	-	<5%
Hydraulic	hybrid pressure/flow differential	1,1÷1,8	4÷8	4÷20 %	-
	conventional pressure/flow differential	5	5	16000	-
	mass(or volume) balance	1	>60	-	-

Table 10. Detection performance on pipeline field applications

A method able to detect a least leakage equal to $1.1 \div 1.8\%$ of the pipe main flow, such as the hybrid pressure/flow differential presented in the previous chapter (*K. Fukushima et al.* 2000, [13]), has an appreciable sensitivity respect to the need of small leakage detection; also the classic mass(or volume) balance method (*J. Doorhy 2011*, [11]) it's asserted to be able to detect leaks even small as 1%.

However both them bases their discrimination capacity, which is the ability to distinguish if what they acquired as a leakage evidence is a real leakage occurring or another issue, on an estimated threshold which is not a certain value, reason why they result to be weak in this sense. In addition pressure flow differential method is characterized by an error on leakage location which in some cases reached 20% making the estimate not suitable.

Concerning the mass/volume balance method we have to say that the 1% reported on the table was a little bit "stretched" as datum: this method works well, i.e. with shorter detection time, with quite higher leakage sizes which however were too large to be compared to the remaining data on that table. For this reason an approximate estimate was done to obtain information about suitable flow percentages, so the response time of $60\ min$ was obtained.
In the context of an integrated pipeline monitoring system a detection requiring more than $60\ min$ is inadequate reason why this method is not that sensitive.

However, since pipeline leakage monitoring systems are integrated systems made by different and complementary detection methods, these two hydraulic methods are still largely used; actually they are the most commonly used model-based leak detection methods in the oil and gas industry.

By observing data reported about field applications of two of the innovative acoustic methods proposed we can realize how these better meet the new small leakages detection needs from pipeline systems industry.

Thanks to the brilliant intuitions they are based on and the extensive researches on the principles on which leak-acoustic generation mechanism relies on, they achieved such encouraging performances of high sensibility, short response time, small location error and low false-alarm rate.

Evaluation indexes of leak detection methods

Detection method	Sensitivity	Location accuracy	False alarm rate	Missing alarm rate	Response time	Adaptability	Cost	Total Score
Mass(or volume) balance method	3	4	4	4	2	2	2	21
Negative pressure method	2	2	4	4	3	1	2	18
Pressure/flow differential method	2	3	3	3	4	1	1	17
Distributed optical fiber	1	2	2	2	2	1	4	14
Recent proposed acoustic methods	1	1	1	1	1	1	3	9

Table 11. Qualitative classification of leakage detection methods

In order to better orientate ourselves within the broad spectrum of leakage detection systems implemented for the pipeline transport industry, Table 11. has been drawn up which collects the main macro-categories of detection methods and makes a qualitative comparison of them using qualitative indexes to describe the aptitude of each category with respect to the specific “skills” in identifying small leakages.
Indexes used in the table goes from 1 to 4: the smaller is the index the greater will be the aptitude of the method in the current “skill”.

As we can observe at the bottom of the table, the innovative acoustic method proposed scored the better mark despite their quite high cost, proving so to be competitive and promising in the specific field.

In light of what have been discussed we can state that the innovative acoustic methods proposed proved to be excellent for an integrated use on leakage monitoring system of modern pipelines, substantially improving the overall detection capacities and leakage management programs.

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