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A Survey of Piping Vibration Screening Methods in Oil, Gas, and Petrochemical Plants

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***Abstract*—Oil, gas and petrochemical facilities are founded on pipeline systems that enable the safe transfer of fluids that are highly pressured, have a high temperature and operate in a complex environment. These systems, however, are very prone to vibration-related issues, including hydraulic and mechanical vibrations such as pressure waves, flow instabilities, acoustic resonance, and rotational equipment vibrations. Over-piping vibration may result in fatigue cracks, fretting effects, leakages, and disastrous failures, which present severe threats to the safety of the plants, their reliability in operation, and the environment. To reduce these risks, vibration screening and monitoring techniques are widely adopted to detect high-risk piping systems earlier and inform maintenance and design decisions. The paper provides an extensive review of the piping vibration problem and the screening method applied in oil, gas and petrochemical facilities. It examines the place of piping systems, causes and processes that lead to vibration-induced damages and the effects of vibration on plant safety and operations. The paper also analyses the current screening, monitoring, and control techniques, such as in-line and off-line inspection, sensor-based monitoring, passive, active and semi-active techniques of vibration control. Comparative review of more recent studies identifies progress, weaknesses and gaps in the research, with the necessity to develop scalable, validated and integrated vibration screening models of industrial piping systems.**

Keywords*— *Piping Vibration, Oil and Gas Pipelines, Acoustic-Induced Vibration, Flow-Induced Vibration, Pipeline Monitoring, Vibration Screening, Petrochemical Plants Pipeline.

I. INTRODUCTION

The Humans' material demands have been a driving force in the petrochemical industry's history and development, which, in turn, has been motivated by these requirements. The petroleum industry first utilized distillation to satisfy the demand for paraffin for residential usage [1]. With the advent of the automobile industry at the turn of the twentieth century came thermal cracking technology. From a small set of fundamental raw materials, petrochemical processes grow into a web of chemicals that eventually converge on compounds with specialized consumer-facing functions [2]. Therefore, the kinds of intermediates and end products needed by both businesses and consumers are the primary determinants of the petrochemical industry's raw material base.

Pipe is the lifeblood of the petrochemical industry since transporting fluids is such a massive undertaking. Hydrocarbons, water, and steam, all at varying temperatures and pressures, are the usual fluids delivered in the petrochemical sector. The proper design of piping systems—which include couplings, valves, gaskets, flanges, and pipes—is essential for the efficient transport of fluids. Connecting various equipment essential to the plant's operation, it is a versatile part of the plant. Most pieces of equipment are rather sturdy and built to last; they often have sturdy foundations, use pipes to link one piece to another, and, when in use, can withstand extremely high temperatures and pressures [3]. The plant's piping system endures almost every harsh environment, including extreme heat, pressure, flow, and sometimes a mix of these. As process growth progresses, the aforementioned issues, together with erosion, radioactivity, toxic conditions, and corrosion, become increasingly intractable in pipe design.

A vital part of the global energy distribution network is the pipelines that transport oil and gas [4]. With predicted increases in oil and gas use over the next few decades, pipeline safety, efficiency, and public image of energy consumption and delivery are of the utmost importance. There are complex oscillations at the interface between the gas and liquid phases in two-phase flows due to velocity differences and contact with the pipe wall [5]. These fluctuations create different two-phase flow patterns, and the resulting vibrations are stronger than those in single-phase flow. When the pipe's inherent frequency is near the frequency of vibration or the frequency of the excitation force from two-phase flow, resonance develops [6]. Pipes may wear out faster, make more noise, and even cause accidents if subjected to critical or excessive vibrations [7]. Another source of pipeline damage is unintentional third-party interference, particularly with subterranean pipes. Criminal acts, such as theft or terrorism, may cause deliberate harm to plumbing infrastructure. Additionally, pipeline integrity may be significantly affected by catastrophic weather events like hurricanes or earthquakes.

The monitoring techniques are methods that are used to constantly monitor and detect pipeline failure once it has occurred, namely by detecting leakage. Sensors that are inserted into or attached to the piping are connected to

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software systems, so that pipeline parameters can be continuously monitored and analyzed. Monitoring systems vary in sensitivity, accuracy, and response time, and may have the ability to find the location of a leak. Periodic inspection methods, on the other hand, are practices used on an intermittent basis for leak detection or to evaluate the condition of pipeline systems [8]. These are generally more intensive than monitoring techniques and can involve physical inspection using various specialized tools

A. *Structure of the Paper*

The following is the outline of the piece: An explanation of Oil, Gas, and Petrochemical Plant Piping Systems is given in Section II. Section III examines the Vibration issues in piping systems. Section IV discusses piping vibration screening methods. Section V discusses related literature and comparative investigations, and Section VI provides a summary of the article and suggests areas for further investigation.

II. Piping Systems in Oil, Gas and Petrochemical Plants

Piping systems are key elements of process facilities, which perform the function of fluid transfer safely and efficiently, and constitute a significant portion of the overall price of industrial projects. The operating pressure, temperature, flow conditions, and other external and dynamic loads control their performance. Failure of critical pipelines in petrochemical plants results in severe cases of leakage accidents, fires and explosions. Thus, risk assessment according to the lifecycle is essential to ensure the safety of the pipeline and its reliability.

A. *Role of Piping Networks in Process Facilities*

Piping Among the most crucial pieces of infrastructure in the modern world, piping systems have been around for centuries and are essential to every civilization's daily operations [9]. They are a system of tubes and fittings used to transfer gas, liquid, or solid materials in suspension. Pipe systems are essential in every sector, but they are especially vital in process industries, where they make up about 20% of the overall project cost, 45-50% of the equipment assembly expenses, and 20% of the installation costs. The pipe: The layout of above-ground pipes is often preferred in industrial installations since it helps with maintenance and may reduce project costs [10]. As a general guideline, while arranging in a parallel fashion at the same height, you should alternate between groups with bigger and smaller diameters. In this approach, the project's cost may be decreased by reducing the number of supports. Ideally, the pipework would be laid out in an orthogonal fashion, with varying altitudes in each direction to facilitate crossings and branches.

An interconnected system of pipes, fittings, and other specialized components used to transport fluids (gas, slurry, liquids, etc.) from one place to another is called a piping system. It is the most efficient way to move fluids, as their properties are preserved or nearly preserved throughout the transfer. Every step of the pipe installation process is carried out in accordance with the rules and regulations set forth by the relevant local authorities and international codes and standards [11]. Here are some common industrial systems that use Piping Engineering:

- The system for piping in buildings
- A System for transferring heat and refrigeration
- One such system is the pipelines that carry and distribute liquids.
- A system for the distribution and transmission of gas
- Electric Pipe System
- System for Process Piping
- System for Transporting Sludge via Pipes

The pipeline systems require a unique design as well as construction planning that meets the required flexibility, in addition to safety and performance of the functionality. The possibilities of the presence of flaws in the design are identified during the initial phase by the application of recent tools, including P&ID diagrams and 3D design systems [12]. The process requires precise coordination to ensure accurate piping isometrics while enabling trouble-free installation. The 3D view of the piping system is shown in Figure 1.

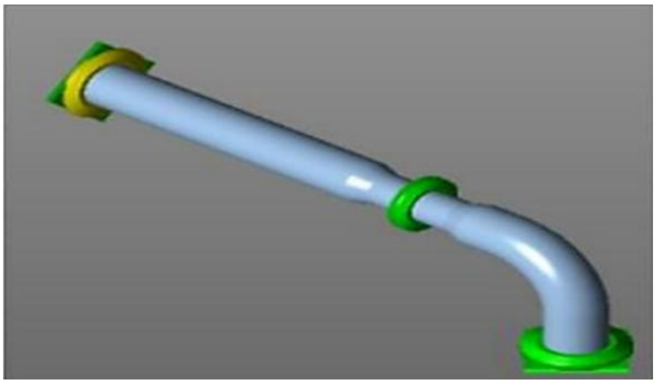

Fig. 1. 3D view of Piping System

B. *Operating Pressure, Temperature and Flow Conditions*

The conditions of operation, temperature and flow of piping systems are important to the safe and reliable operation of piping systems, particularly in the process of petrochemical plant revamping and process reconversion [13]. The change in these parameters directly affects structural integrity, failure hazard and operational continuity.

- **Plant Revamping Drivers:** Petrochemical plants are being motivated by increasing fuel costs, environmental concerns and decreasing demand for refined oil products to reshape their processes to produce alternative and sustainable sources of energy.
- **Importance of Piping Systems:** Piping systems are specifically sensitive when revamping a plant because they are the core of the process operations and contain many interrelated parts [14].
- **Safety and Failure Risks:** The failure of one piping item will cause unplanned shutdowns of the plant and can be extremely dangerous to the life and overall safety of people.
- **Key Failure Classification Factors:** In gas pipelines, the most significant factors that affect the classification of failures are wall thickness, material characteristics, operating pressure, and the location of the pipeline; thus, balancing in the design is necessary.
- **Pressure and Temperature Loads:** The piping systems are exposed to self-weight, internal media pressure, and high wall temperature load conditions in normal operations.
- **Flow-Induced and Environmental Effects:** Fluid flow dynamic loads and seismic, wind and

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environmental loads may cause significant changes in the behavior of piping systems with variations in operating pressure, temperature and flow conditions.

C. Critical Pipeline Services, Leakage Accidents, and Risk Management

The transportation of petroleum products via oil and gas pipelines (OGPs) is a safe method, but several risks may lead to pipeline collapse [15]. Damage from corrosion, natural disasters, operational errors, and Third-Party Disruption (TPD) are the most common problems affecting OGPs.

The frequency of accidents in petrochemical complexes caused by chemical leakage has been on the rise. Serious harm to people and widespread disasters like fires and explosions might result from these occurrences. Within a certain concentration range, a combustible substance that has spilled out might trigger an explosion. Areas, neighboring facilities, and lives might all be impacted by an explosion. The energy released by an explosion travels through the air as blast overpressure and the earth as impact load. Explosive force, local factors, and distance all contribute to an explosion's destructive potential.

1) Gas Leak Accident Cases

Noncompliance with safety regulations or facility flaws are the most common causes of gas leaks in petrochemical facilities. Damage to process lines, including failure, degradation, and corrosion, is the leading source of leakage among facility faults. The process pipe has split during filling in the past, leading to accidents [16]. Damage to the vicinity of the broken pipe weld was initially thought to be the cause of the accident. During this process, sparks ignited hydrocarbon gas that had spilled and combined with atmospheric oxygen. Also, since gas has a limited electrical conductivity, it might catch fire from static electricity if it floats or rattles. When these elements come together, they may increase the likelihood of explosions.

Pipeline Risk Assessment: To achieve complete management of the pipeline's safety, it is necessary to conduct risk assessments on oil and gas pipelines on a regular basis during the operation period, improve the defect factors identified in the assessments in line with standards or requirements, and finally complete the assessments [17]. Therefore, a risk assessment must be carried out at some point over the pipeline's longevity. The pipeline's safety and the validity of maintenance and upgrading choices are its primary objectives.

III. Vibration Issues in Industrial Piping

The vibrations are primarily caused by hydraulic and mechanical excitation, e.g., pressure pulsations, flow instabilities and vibrations as conveyed by rotating equipment. These excitations may couple with acoustic and structural natural frequencies, resonate and cause increased dynamic stresses. Fretting and fatigue cracking of the metal are experienced after prolonged exposure to such conditions, especially at welds, supports, and branch connections. Therefore, high vibration of the pipes is a serious threat to the plant's safety, reliability, and continuous operation [18].

A. Sources of Vibrations in Process Plants

Mechanical and hydraulic factors are the most common causes of pipe vibration. Sometimes, hydraulic vibration sources are called Fluid-Induced Vibration (FIV) or Acoustically Induced Vibration (AIV). This kind of vibration is caused by very high-pressure variations in a compressible flow stream and is experienced by structures. Pressure pulsations are among the most prevalent causes of industrial pipe vibration. Fluids in motion in pipes may induce deflection under specific flow conditions due to the oscillating pressures exerted on the pipe walls [19]. Due to this pipe displacement, the piping system's structural stability may be compromised.

1) Common Causes of Vibration in Piping Systems

Two main categories of stimulation can cause pipe vibration: hydraulic and mechanical.

- **Hydraulic Stimulation:** This type of stimulation can manifest in a variety of ways, including pulsations, turbulence, periodic flows, cavitations, flashing, water-hammer, and surge. Its main effect is to induce flow instabilities in pipes by transferring the fluid's dynamic pressure to the pipe wall, which in turn causes the pipes to vibrate internally.
- **Mechanical Excitation:** Mechanical components that vibrate, including motors, pumps, compressors, equipment foundations, or mechanical coupling, may provide mechanical excitations to piping systems via connections in the pipes.

Fluids experience pressure pulsation when there is a shift in the applied force at a change in the geometry of the pipe, such as at an elbow or other pipe fitting. Similar to how fluids in pipe systems display an acoustic natural frequency, the idea of structure exhibits a structural natural frequency. Therefore, acoustic natural frequency has the potential to increase the pulsation from a low to a high-pressure level in the pipe system. A pipeline system's acoustic natural frequency is heavily dependent on the pipe diameter and process conditions. In real-world applications, pulsation in piping systems is most commonly caused by centrifugal pumps, compressors, and reciprocating or positive displacement pumps. Several factors contribute to this, such as imbalances in the fluid flow induced by variables including impeller rotation speed, geometry of the wheel, process parameters, and the shape of the volute.

B. Vibration-Induced Damage and Failure Mechanisms

The primary mechanisms contributing to vibration-induced fatigue failures in gas processing pipelines arise from fluid-dynamic forces, acoustic excitation, mechanical oscillations, and structural design weaknesses. Flow-induced vibration (FIV) occurs when turbulence, vortex shedding, or slug flow interacts with the pipe wall, creating alternating cross-stream pressure forces. These cyclical forces can produce oscillations at characteristic frequencies, especially in long unsupported spans or sections with abrupt changes in geometry [20]. Due to high-velocity streams, vortex shedding should be harmonized with the structural natural frequency to lead to resonance, which contributes greatly to the magnitude of stress cycles on the pipeline.

Another significant contributor is acoustic-induced vibration (AIV), especially in high-pressure gas systems, whereby pressure pulsations are caused by control valves, blow-down operations or compressor discharge. AIV produces high-frequency, low-amplitude stress waves that travel very rapidly along the path of the pipeline and produce very rapid fatigue crack propagation, particularly in thin-

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walled sections or branch connections. Compressors and rotating machinery also add mechanical vibrations to the pipeline, introducing harmonics that can overlay the fluid-dynamic vibrations to give complex multi-frequency loading patterns.

Fatigue susceptibility is also caused by structural factors. Welded joints, gussets, pipe supports and attachments are stress concentrators at which the cracks normally start. Lack of support or ineffective support of the pipeline increases the vibrational energy, and the rigid supports may reflect the vibrations instead of dissipating them. Additionally, operational conditions such as sudden flow transitions, valve closures, and multiphase slugging can dramatically increase dynamic loading. Over time, the combination of these forces leads to fatigue crack initiation at microscopic flaws or imperfections, followed by progressive crack propagation governed by cyclic stress intensity.

C. *Impact on Plant Safety and Operations*

Industrial process pipes connected to large-flow gas systems are prone to fatigue failures within minutes or hours when exposed to vibrations induced by high-frequency acoustic stimulation of high-pressure letdown devices. This process is often referred to as Acoustically Induced Vibration (AIV) [21]. Pipe fatigue and fretting are two phenomena that may be caused by vibrations in pipe systems. Pipe fatigue causes cracks to form in walls and pipes, with welded joints being the most vulnerable areas. As a result of fretting, which occurs when two surfaces move relative to one another, one or both surfaces may wear down, and the fluid inside the pipeline will leak out.

In industrial plants, process piping subjected to the vibrations induced by high-frequency acoustic excitation of high-pressure letdown devices, associated with large-flow gas systems, may lead to fatigue failures within a few minutes or hours. This mechanism, well known as Acoustically Induced Vibration (AIV)

In pipe systems, fatigue failure may occur due to high-frequency AIV, particularly in big-bore piping with relatively large diameter-to-thickness ratios [22]. Fatigue failure might occur at locations where these pipe systems have asymmetric welds. Geometric discontinuities, such as asymmetric welds, create stress concentration areas known as "AIV-critical locations." The following are among them:

- Branches that are linked
- Connecting a few branches
- Supports for welded pipes

Although the welds are excellent (i.e., there is no misalignment, undercut, or other bad joint features), technical studies on AIV-related pipe failures have not documented any failures in straight pipes. Hence, until the circumferential and longitudinal butt welds connected to a straight pipe meet the standards established by the relevant piping code, it does not matter how high the sound power level is or what the diameter-to-thickness ratio is; such locations are not AIV-critical.

IV. Piping Vibration Screening Methods

To avoid their collapse and the consequences that might follow, pipeline monitoring is seen as an important preventative strategy. Potential dangers include leaks, corrosion, or structural damage. Failure of the system, which in turn causes resource loss, pollution, and financial losses, could result from these risks being undervalued. Technologies that include real-time pipeline information are a part of modern surveillance systems. Examples of such technologies include acoustic devices, fiber optic sensors, and IoT networks [23][24]. Because of this, the system will be able to make decisions on the go, which makes it more efficient and effective.

Pipeline monitoring is a crucial technique that ensures the reliability, safety, and proper operation of pipelines that transport various substances, including water, oil, petrol, and gas. When designing monitoring systems, it is crucial to consider several key factors.

A. *Screening Methods*

1) *In-Line Inspection (ILI)*

It involves inspecting the pipeline from the inside using certain instruments to determine its condition. Among these problems are corrosion, fissures, and obstructions. Methods for finding leaks include electromagnetic acoustic testing, ultrasonic testing, eddy-current testing, and magnetic flux leakage testing.

2) *Off-Line Inspection (OLI)*

The process of offline inspection. When a pipeline is not in use, it may be inspected for issues, including interior corrosion, fractures, and obstructions. It is necessary to conduct this type of inspection when the pipeline is not in service, and a manual inspection is required.

3) *Technologies and Techniques for Pipeline Monitoring:*

A variety of factors, including environmental impacts, building flaws, physical strikes, and others, may cause pipeline abnormalities. Issues like leakage or faulty installation are examples of such irregularities. In addition to determining what caused the abnormality, detecting its occurrence has a significant impact on pipeline operations.

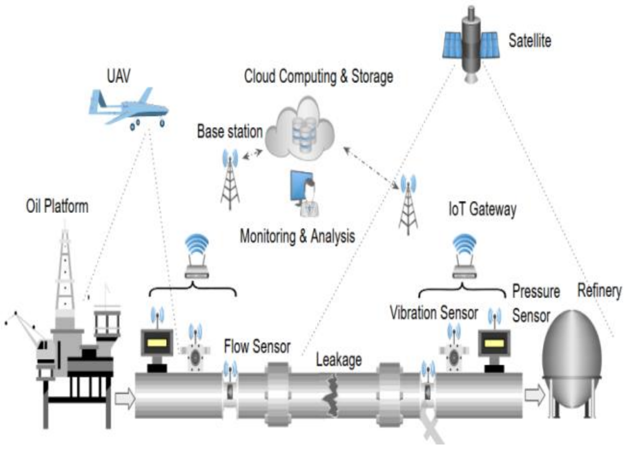

Fig. 2. An overall view of Pipeline Monitoring System

The proper functioning and integrity of pipelines can only be ensured with the use of pipeline monitoring systems. The majority of these technologies rely heavily on data sensing, acquisition, and transmission. In the case of pipelines, modern technology has enabled efficient monitoring of activities across vast regions. Sensors that use sound or ultrasound, as well as pressure or fiber optics, and other wireless technologies, are examples of these contemporary innovations [25]. The primary components of a monitoring system are shown in Figure 2.

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a) Ultrasonic and Acoustic Sensors

Pipeline leaks, fractures, or other abnormalities may often be detected using acoustic sensors, which are highly effective at detecting changes in sound or vibration. A vibrational or auditory impact is created when fluid (gas, oil, water) escapes via a fracture or hole in a pipeline. Broadband optomechanical ultrasonic sensors with high sensitivity to detect and analyze acoustic signals produced by nitrogen gas emitted from tiny syringes under pressure. There is a constant stream of new developments in sensing technology pertaining to the physics of acoustics, especially in the ultrasonic high-frequency domain [26]. As a function of flow conditions, it finds jet tones that are harmonically connected in the MHz frequency range. Enhanced turbulent flows were found to produce broad-spectrum ultrasonic emissions, reaching up to 5 MHz. The created sensor simultaneously exhibits omnidirectional behavior, high sensitivity, and a wide bandwidth. These final requirements ensure the reliable identification of high-pressure gas leaks, regardless of their off-axis or off-position locations.

When working with liquids, hydrophones may be quite useful. What are often called "underwater microphones" are really quite basic acoustics sensors [27]. They are often linked to pipelines that transport liquids and to submerged pipes. Hydrophones produce slower signal variations with fewer identifiable peaks, as they operate as low-pass filters. Alternatively, sensors for acceleration and velocity function as Bandpass filters, resulting in more pronounced peaks. Because of this dissimilarity, the mixed system's cross-correlation functions are unique from those of the two kinds of functions. When used together, the sensors can pinpoint both the exact moment of a leak and its precise location.

b) Pressure Sensors

Monitoring pressure enables operators to detect disruptions, structural deterioration, leaks, and obstructions. A pipeline's pressure profile represents the typical pressure fluctuations in a properly operating pipeline. Several variables affect the pressure profile, including the low rate, the pipe diameter, the contents (gas or water, for example), and the pipeline's elevation. Any reading that deviates significantly from the expected range of the pipeline's pressure profile is considered a possible abnormality.

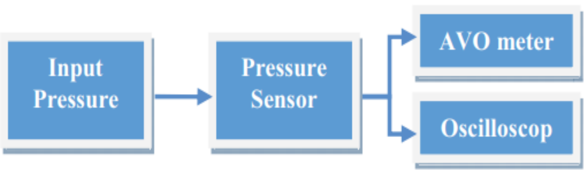

Fig. 3. Block diagram testing pressure sensor output

Various techniques exist for monitoring pipeline pressure. One approach relies on monitoring pipeline static pressure under typical operating conditions. A slow leak might be indicated by small pressure variations. Among these methods is the NPW (Negative Pressure Wave) approach. A pressure wave travels both upstream and downstream in the event of a breach. When waves are generated and monitored for arrival at pipeline sensors, the precise position of the leak can be determined. I) This method is inexpensive, and (ii) it allows for monitoring that is almost instantaneous. Among the drawbacks are the following: (i) dealing with data that is prone to noise; and (ii) distinguishing between pressure fluctuations that need leak reporting and those caused by operational differences, such as pump action. An essential issue to resolve is the distinction between a leak and a temporary occurrence. As shown in Figure 3, the voltage output of the sensor is tested using a block diagram [28].

c) Fiber Optic Sensors

Fiber-optic sensors enable continuous, real-time tracking. They can be located outside the pipeline, within the insulation, or buried beside the pipeline. Because of this, fiber optics can detect and track any change that can compromise the pipe's structural integrity [29]. Using fiber-optic sensors, one can detect vibrations and audio signals that may indicate an invasion or construction. It is common practice to install optical fiber sensor systems in permanent places [30]. Therefore, an optical fiber network must be formed by connecting all the sensors using lengthy fiber-optic cables, which may be both expensive and inconvenient.

B. Vibration Control Methods

Maintaining security, prolonging system lifetime, and assuring smooth operations in oil and gas pipeline networks: that is the mission of vibration control. Figure 4 shows a pipeline system that may use the following technologies for vibration control [31]:

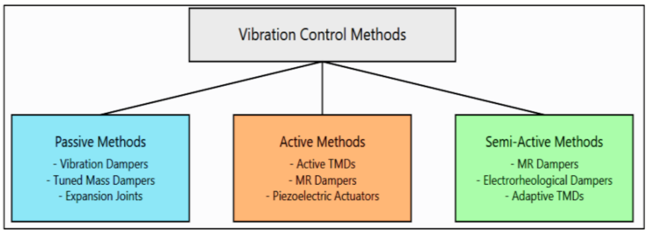

Fig. 4. Methods of Vibration Control in Pipeline Networks

1) Passive Vibration Control Methods in Pipeline Networks

Vibration management in oil and gas pipeline networks is very important for ensuring safety, the longevity of composite systems, and the efficient functioning of the system. Passive vibration control techniques are typified by the use of equipment, systems, or machines that absorb, damp, or restrict vibrational energy without requiring active input or control. Low-frequency vibration cannot be actively controlled using passive vibration control, and the control parameters are not controllable as the excitation environment varies [32].

- One more popular option is vibration dampers, which use materials like rubber or silicone to absorb the energy of vibrations via internal dampening mechanisms. Some of these devices, such as viscoelastic dampers, reduce the energy transmitted through a pipeline by converting vibrational energy into heat.
- A secondary mass in tuned mass dampers (TMDs) is adjusted to the natural frequency of the pipeline, which inhibits vibrations via destructive interference. This effect is similar to the first effect. Supports and restraints for pipes, such as spring supports and U-bolts, provide additional structural integrity by preventing unnecessary movement and holding pipes in place.
- Expansion joints, which should be able to absorb vibration due to thermal expansion or motion caused by flow, are flexible and at the same time do not impair the structure. Lastly, isolation pads, constructed of

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rubber or elastomeric materials, may be installed in the supports of pipes to limit vibrational energy transfer to surrounding structures.

The combination of these passive techniques aids in effective handling of vibrational forces within the pipeline networks, thus leading to safety, compliance and efficient operations.

2) Active Vibration Control Methods in Pipeline Networks

The active vibration control (AVC) technique is a highly developed technology in the oil and gas sector that aims to control the vibration of oil and gas pipes through an adaptive approach that dynamically reacts to changes in vibration

- **Active Tuned Mass Dampers (ATMDs):** This represents a considerable improvement to the passive tuned mass dampers, whereby the sensors and the actuators control the response continuously, by responding to the real-time vibration frequencies, to provide the optimal damping response.
- **Another cutting-edge approach is the use of magnetorheological (MR) dampers:** These dampers adapt their damping properties to different operating conditions by exploiting the fact that fluid viscosity can be precisely controlled by an external magnetic field.
- **Piezoelectric Actuators:** By converting electrical impulses into mechanical movements, these actuators exploit the piezoelectric properties of certain materials to provide counteracting forces that cancel vibrations.

These active types of controls provide better vibration control capability as they allow real-time adjustment and thus are effective, especially in dynamic settings where the vibrational forces vary with the flow rates, operating conditions or any other external disturbances. Active vibration control converts e. g. a mechanical force externally by use of actuators [33]. This is the mechanical force which is utilized to actively reduce the vibrations in a controlled way as in Figure 5.

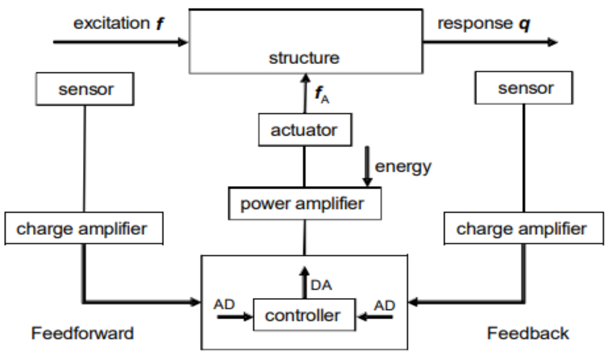

Fig. 5. Components of a system for active vibration control

3) Semi-Active Vibration Control Methods in Pipeline Networks

To effectively manage vibrations, semi-active systems combine the best features of passive and active approaches; they can adapt to varying vibratory conditions without continuously drawing power from an external source [34].

- Electrorheological and magnetorheological (MR) dampers are examples of semi-active control devices that may adapt their damping characteristics in real-time based on vibration frequency measurements, allowing for responsive control that meets operational needs. These devices effectively reduce vibrations while minimizing energy consumption by manipulating the damping properties of their materials using electric or magnetic fields.
- ATVAs, which stand for "adaptive tuned vibration absorbers," enhance the efficacy of semi-active controls by providing damping solutions that can dynamically adapt to different vibratory circumstances. The efficiency of vibration mitigation is enhanced by ATVAs, which fine-tune their responses in real time, stabilizing the system and safeguarding pipeline infrastructure and equipment.

The flexibility of the active scheme and the energy savings of the passive scheme in the semi-active approach make it a more popular choice in contemporary pipeline network layouts, particularly where vibration control is required with high reliability and low cost. Figure 6 demonstrates the application of the MR Damper.

Fig. 6. MR Damper Application

V. Literature Review

Recent works in the areas of pipeline vibration, leakage detection, and monitoring are discussed in this part, including data-driven signal analysis, hydraulic and robotic inspection, SHM, and an Internet of Things-based framework. The works emphasize enhanced pipeline safety and real-time monitoring and fault detection in industrial applications.

Tao et al. (2025), an enhanced sparrow search algorithm-correlation variational modal decomposition (ESSA-CVMD) and entropy assessment method for pipe leakage. First, the penalty factor and the order of modal decomposition were optimized by enhanced SSA step factor. In this way, the pipe vibration signal could be filtered according to the correlation between the intrinsic mode function (IMF) and the original signal. Then, the multiparameters of vibration signals were extracted. Furthermore, the membership matrix was constructed by means of the self-information of conditional entropy. The leakage level of the pipe could be assessed through the fuzzy calculation of the weight vector and membership matrix. The numerical simulation and experiment showed that this data-driven method could monitor and assess the leakage state of the pipe [35].

Popov et al. (2025) present a methodology for determining the equivalent length Le of the most commonly encountered complex pipe systems. This methodology has been developed based on an original method for the hydraulic calculation of

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pipelines using critical equations that are generally valid for different flow regimes of fluids in pipes. A key advantage of the proposed methodology for determining. It eliminates the need for iterative methods to calculate friction losses. Its application requires only the geometric parameters of the pipeline sections (diameter, length, and equivalent roughness), as well as the coefficients of local resistances included in them. This makes the methodology universally applicable to all fully developed turbulent flow regimes of fluids in piping systems [36].

Chen et al. (2025) present a novel detection system comprising the Pipeline All-aspect internal Surface defect Spiral detecting robot and an interactive visualization software. After testing at the SSPs factory, the system delivers comprehensive, wireless, and efficient detection and visualization for ISDs. In addition, they construct a dataset for ISDs in SSPs, named SSP2000. The dataset contains 2000 images across nine defect categories, presenting many challenges. Specifically, they first use the synergize perception augmentation module to enrich the feature space and to enhance perception. Then, the hierarchical attention integrate module merges deep and shallow features using adaptive attention weights. Finally, the bilateral self-fusion module fully exploits intralayer features and produces prediction results [37].

Qi et al. (2024), The abnormal vibration of the pipeline seriously threatens the safety in nuclear power plants, which is related to the design, commissioning and operation phases. The capacity to identify negative structural changes—and hence improve structural dependability and life-cycle management—has led to its widespread use across many engineering domains, where structural health monitoring (SHM) systems are used. This article applies the SHM method to pipeline vibration problems in the nuclear power industry. Based on the existing regulations, standards and industry practices, the framework of the pipe vibration monitoring system is proposed, and the associated algorithm is studied [38].

Achimugu et al. (2024) The RePIMOS system, which employs the Wireless Sensor Network (WSN) technique, is a monitoring system for pipelines from a distance. By detecting leaks in real-time, RePIMOS can stop pipeline vandalism and damage in its tracks. Created sensor nodes may detect motion and vibrations in the pipeline's immediate vicinity and record them in real time. The data obtained is sent to the cloud by the master node with the aid of the ESP8266 microcontroller, and is accessible by authorized personnel for prompt action. A 300-millisecond vibration shock pulse and motion detection are indicators of damage, according to the research. This finding was reached after applying various impact levels to a 100m water pipeline test bed at the Pipeline Monitoring Research Center, Federal University of Technology, Minna, where RePIMOS was tested [39].

Quamar, Khan and Khalid (2023) The oil and gas (O&G) sector has seen rapid expansion in recent years, with exponential growth predicted for a wide range of activities, including upstream and downstream operations, fault management, and monitoring. Compared to manual wired/wireless solutions, the sophisticated ones made possible by LPWAN and the cloud are far better. One of the most exciting developments in low-power wide-area networks (LPWAN) is narrowband internet-of-things (NB-IoT), which has the potential to greatly improve QoS, latency, reliability, range, cost, and battery life. Taking into consideration the benefits of NB-IOT, this study presents a framework for integrating NB-IOT with the most popular cloud technologies for O&G industry defect detection and monitoring [40].

Table I compares the recent approaches to the issue of pipeline vibration, leakage, and monitoring based on the data-driven, hydraulic, SHM, robotic, and IoT-based methodologies.

TABLE I. COMPARATIVE ANALYSIS OF PIPELINE VIBRATION, LEAKAGE, AND MONITORING APPROACHES

Reference	Focus Area	Key Findings	Challenges	Key Contribution	Limitations / Gap
Tao et al. (2025)	Data-driven pipe leakage assessment using vibration signals	ESSA-CVMD combined with entropy and fuzzy assessment effectively filtered vibration signals and accurately assessed leakage levels	Optimal parameter selection and handling complex vibration noise	Proposed an intelligent vibration-based leakage assessment framework with high monitoring accuracy	Computational complexity; validation limited to controlled simulations and experiments
Popov et al. (2025)	Hydraulic analysis of complex pipe systems	Developed a universal method to compute equivalent pipe length without iterative friction loss calculations	Applicability under non-fully developed or transient flow conditions	Simplified hydraulic calculation methodology applicable to turbulent flow regimes	Does not address vibration, leakage detection, or real-time monitoring aspects
Chen et al. (2025)	Internal surface defect detection in pipelines using robotics and deep learning	Proposed an automated inspection system with SRPCNet, achieving accurate multi-class defect detection	Handling complex defect patterns and deployment in diverse pipeline environments	Introduced SSP2000 dataset and an advanced deep learning model for internal defect detection	Focuses on visual inspection; vibration-related damage mechanisms not considered
Qi et al. (2024)	Pipeline vibration monitoring in nuclear power plants	Demonstrated effectiveness of SHM-based real-time vibration monitoring to ensure operational safety	Integration with existing standards and real-time deployment complexity	Proposed a comprehensive SHM framework tailored for high-risk pipeline vibration scenarios	Application limited to nuclear industry; scalability to other sectors not validated
Achimugu et al. (2024)	Remote pipeline leakage and damage monitoring using WSN	Real-time vibration and motion sensing successfully detected leakage and vandalism events	Sensor reliability, energy management, and large-scale deployment	Developed the RePIMOS system, integrating vibration harvesting and cloud-based monitoring	Tested on limited pipeline length; long-term robustness unverified
Quamar, Khan and Khalid (2023)	IoT-based fault detection and monitoring in oil and gas pipelines	NB-IoT and cloud integration improved fault detection reliability and reduced operational cost	Network latency and dependency on cloud infrastructure	Proposed a scalable NB-IoT–cloud framework for pipeline monitoring in the O&G industry	Lacks experimental validation using real vibration or leakage datasets

VI. Conclusion and Future Work

Vibration of pipelines is a severe issue in oil, gas, and petrochemical plants, as the interaction of hydraulic excitations, mechanical disturbances, and structural properties of piping networks is rather complicated. This survey has discussed the role of industrial piping systems, the origin of the major sources of vibrations, including flow-induced and acoustic-induced mechanisms as well as the role of vibration in fatigue damage, leakages and malfunctioning of the system. The analysis of the vibration screening, monitoring, and control practices shows that the timely detection of vibration risks must be one of the primary goals of preventing disastrous accidents and ensuring the reliability of the plant. The existing methods, such as inspection-based methods, sensor-based monitoring, passive, active and semi-active vibration control, have proved to be effective in anomaly detection and reduction of vibration-induced damage. Nevertheless, the comparative study of recent literature indicates that there are limitations associated with computer complexity, sector-specific applicability, scalability, and lack of field and long-term validation. These loopholes indicate the necessity of common screening criteria and combined frameworks that comprise monitoring, analysis, and decision support. On the whole, this paper highlights that the successful screening of piping vibration is one of the main facilitators of enhancing safety, increasing service life, and minimizing maintenance expenses in industrial process plants. Future studies are needed to come up with integrated and quantitative vibration screening models that incorporate real-time monitoring, data-driven analytics, and lifecycle risk assessment. There is a need to focus on field validation on a large scale, cross-industry application and digital twins and machine learning integration to improve predictive capability and decisions in industrial piping systems.

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