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MATHEMATICAL AND EXPERIMENTAL INVESTIGATION OF VIBRATION ISOLATION CHARACTERISTICS OF NEGATIVE STIFFNESS SYSTEM FOR PIPELINE

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ABSTRACT

The technological advancement in both upstream and downstream industry has ensured safe handling and transfer of products (specially Oil, gas and petroleum) in both offshore and onshore part of business. The life cycle of pipeline depends on several negative parameters that caused by nature or system that where it is involved. Amidst all these life decaying factors, vibration is one of the significant reasons for which reliability and efficiency of pipeline and its associated equipment are being vulnerable day by day. Here in this dissertation, vibration in pipeline will be analyzed both in mathematically and experimentally before and after addition of negative stiffness system in the respective pipeline. After project phase accomplishment of a plant, the pipeline and its ancillary equipment (valves flange-flange joints, pneumatic and hydraulic parts, electrical cum instrumental devices), machineries (pump, compressor, motor), structures etc. remain safe and secure during operational handling of product if the negative factors specifically vibration is appropriately isolated or not. Vibration exerts a potential negative influence on both the transfer equipment and surrounding entities. The basic source of vibration is rotor. A multitude of various harmonics exist the vibration spectrum of actual product transfer unites and mainline pumps. During operations, region of resonance conditions constantly deviates, impact of vibration is observed highly significant during machineries are shut down and when it is started as well as hydrodynamic impact of mass flow through respective pipeline. The development of Negative Stiffness system for vibration isolation is therefore required to maintain safe and secure pipeline and its related units. This study involves construction of an experimental bench and pipeline with which to

investigate systems with negative stiffness system as vibration isolators. The design, computer model, practically experimented data consists of elastic springs, serving as negative stiffness compensators. Normally the performance of conventional vibration isolation systems is specified by mounted stiffness required to support the weight of payload. Here the negative stiffness helps by resulting high static stiffness to support weight of payload and low dynamic stiffness to achieve significant vibration isolation bandwidth. This study exhibits the reduction of frequency and vibration of pipeline system by adding negative stiffness system with the main structure.

1 INTRODUCTION

All vibrations, more or less important to human safety and comfort, are in the frequency spectra, which can be symbolically divided into the ranges close to 0 Hz, < 10 Hz, and 10-100 Hz. This paradigm exists due to the human body that remains mostly invariable and, at the same time, due to variability and huge trend to a certain miniaturization of the machine mechanisms and other aids generating and transmitting the vibrations to humans. This is determined with the dimensions, shape, other specifics of elastic and dissipative elements, and spatial location of a negative stiffness system (NPS) inside or outside the machine, pipeline or integrated piping and instrumental system (Kashdan et al., 2012). The above ranges become critically important, as new objects appear that require high quality of the infra-low vibration protection in the first place, such as in bioengineering and medical research, in micro- and nanoelectronics, and in transport vehicles such as high-speed trains, helicopters, nanosats, and other modern and next generation machines. This is clear when considering a key parameter of a NSS, namely, its natural frequency spectra, which are changed as the NSS structure and geometry features and other characteristics are changed (Dong & Lakes, 2012). For instance, the natural frequency of a single-degree-of-freedom (1DOF) NSS is f0 = (2n : ' \ nggz01 (1-1) wheref0 is the natural frequency of undamped NSS, ng 2 (0; 1] is the coefficient of gravitation, g « 9.81 (m/s2), and z0 (m) is the parameter determining the system travel in a direction of vibration motion. This research aims to analyze the effectiveness of a Negative Stiffness System (NSS) in mitigating vibrations within pipeline networks. The study will compare vibration characteristics, such as displacement, velocity, and acceleration, in pipeline sections both with and without the implementation of NSS, focusing on vibrations induced by fluid flow and mechanical equipment like motors. By identifying the differences in vibrational impacts during these stages, the research seeks to establish NSS as a superior solution for reducing fatigue, enhancing structural integrity, and extending the operational lifespan of pipelines under varying conditions. The insights gained from this study aim to contribute to safer, more reliable, and cost-effective pipeline operations.

2 LITERATURE REVIEW

The control of vibrations in pipeline networks has garnered significant attention in the oil and gas industry due to the critical role pipelines play in transporting resources safely and efficiently. This section explores existing research on vibration sources, impacts, and control methods, with a focus on advanced solutions like Negative Stiffness Systems (NSS). Key topics include the limitations of traditional vibration control methods, the mechanics and benefits of NSS, and their application in mitigating flow-induced, acoustic-induced, mechanical, and environmental vibrations. By synthesizing findings from past studies, this review establishes a foundation for understanding the need for innovative vibration control mechanisms and highlights gaps in current research, which this study seeks to address.

2.1 Effects of Vibration for Pipeline

Vibration in a pipeline network can occur for various reasons, and it's essential to identify and address the root causes to prevent damage and ensure the efficient operation of the system (Li et al., 2015). Here are some common reasons for vibration in pipeline networks:

Fluid Flow:

- **Turbulence:** High flow rates or abrupt changes in pipe geometry can lead to turbulent flow, causing vibrations.
- **Water Hammer:** Rapid changes in fluid velocity, such as sudden valve closures, can create pressure waves, leading to vibration.

Mechanical Factors:

- **Pipe Supports:** Inadequate or improperly designed pipe supports may result in excessive movement and vibration.
- **Misalignment:** Misalignment of pipe sections, equipment, or supports can induce vibrations.
- **Pipe Sagging:** Sagging of long spans of pipeline can cause vibrations due to the additional weight and flexing.

Resonance:

- **Natural Frequency:** If the frequency of fluid flow or other external forces coincides with the natural frequency of the pipeline, resonance can occur, leading to vibrations.

Equipment Issues:

- **Pump or Compressor Imbalance:** Imbalanced rotating equipment can transmit vibrations to the pipeline.
- **Mechanical Wear:** Wear and tear on rotating equipment can lead to imbalance and vibration issues.

Cavitation:

- **Cavitation in Pumps:** If the pressure of the fluid falls below the vapor pressure, cavitation can occur, resulting in vibrations and potential damage to the pipeline.

External Forces:

- **Seismic Activity:** Earthquakes or other ground movements can introduce external forces, causing vibrations in the pipeline.
- **Traffic or Construction Vibrations:** Nearby construction activities or heavy traffic can transmit vibrations to the pipeline.

Thermal Expansion and Contraction:

- **Temperature Variations:** Fluctuations in temperature can cause thermal expansion or contraction, leading to stress and potential vibration.

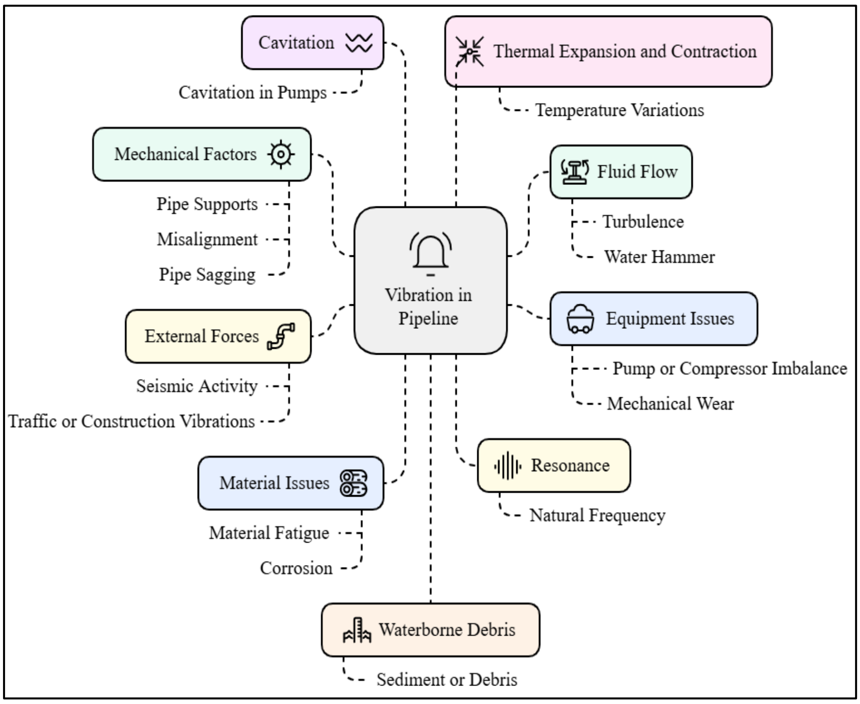
Material Issues:

- **Material Fatigue:** Over time, materials may experience fatigue, leading to structural issues and vibrations.
- **Corrosion:** Corrosion can weaken the structure of the pipeline, making it more susceptible to vibrations.

Waterborne Debris:

- **Sediment or Debris:** Accumulation of sediment or debris within the pipeline

Figure 1: Effects of Vibration for Pipeline



can disrupt the flow and induce vibrations.

Pressure Fluctuations:

- **Pressure Surges:** Rapid changes in pressure within the pipeline can lead to vibrations (See figure 1)

2.2 Significance of this thesis for pipeline network of all Industry

Addressing vibration issues in pipeline networks across various industries necessitates a comprehensive approach that includes vibration monitoring, analysis, and the implementation of effective mitigation measures. A negative stiffness system (NSS) emerges as a crucial solution to manage dynamic forces and vibrations effectively. The design of an NSS involves several critical considerations, starting with a detailed vibration analysis to identify frequencies and amplitudes, which inform the required stiffness characteristics (Kumar et al., 2003). Material properties, such as stiffness and damping, are pivotal in shaping the system's response to vibrations, necessitating a thorough understanding of the pipeline and support materials (Li et al., 2015). Fluid dynamics, including flow rates, pressure fluctuations, and potential water hammer effects, significantly influence the NSS design, ensuring it can address dynamic forces effectively (Song et al., 2016). Additionally, the pipeline's geometry, encompassing length, diameter, and configuration, affects natural frequencies and vibration modes, which must be accounted for in the design (Wang et al., 2017). Operating conditions, such as temperature and pressure variations, further impact the NSS performance, requiring designs adaptable to these fluctuations (Kumar et al., 2003). The desired frequency response of the system must be clearly defined to target dominant vibration modes effectively. Understanding dynamic loads generated by equipment like pumps and compressors is essential for designing an NSS that can counteract these forces (Ibrahim, 2008). Compatibility with existing supporting structures and regulatory compliance are also vital considerations, ensuring the system aligns with safety standards and operational regulations (Kang & Mori, 2017). Cost-effectiveness and feasibility, including installation complexity and maintenance, must be weighed alongside the need for environmental resilience to factors such as seismic activity and external vibrations (Huo et al., 2011). Finally, incorporating system adjustability allows for tuning and adaptability to evolving operating conditions, enhancing long-term reliability and efficiency. In this context, a well-designed NSS not only ensures pipeline stability and performance but also contributes to the sustainable and safe operation of industrial pipeline networks (Ibrahim, 2008).

2.3 Benefits of Negative Stiffness Systems

Implementing a negative stiffness system (NSS) in a pipeline network offers significant advantages, primarily in mitigating vibrations and dynamic forces. By reducing vibrations caused by fluid flow, equipment operation, or external disturbances, an NSS ensures smoother and more stable pipeline operation (Kaloop et al., 2016). This reduction in dynamic forces protects sensitive equipment such as pumps, compressors, and valves, extending their lifespan and minimizing the likelihood of mechanical failures (Kashdan et al., 2012). Additionally, the system helps prevent fatigue and wear in pipeline components, reducing the need for frequent maintenance and repairs, which can be costly and time-consuming. Improved system reliability is another critical benefit; with reduced vibrations, the risk of unexpected disruptions or failures is significantly decreased, contributing to more consistent operational performance (Kim & Adeli, 2005). Enhanced safety is a further outcome, as vibration-induced stresses can compromise structural integrity, while an NSS reduces these stresses, creating a safer operating environment. Furthermore, compliance with industry-specific regulatory standards is often achievable through vibration mitigation, avoiding potential penalties and ensuring adherence to stringent safety requirements (Ibrahim, 2008).

In addition to mitigating vibrations, a negative stiffness system can enhance operational efficiency and provide long-term economic benefits. By reducing dynamic forces, the system improves fluid flow within the pipeline, lowering energy consumption and optimizing overall performance (Kaloop et al., 2016). This enhanced efficiency contributes to cost savings, as equipment experiences less wear and tear, extending the lifespan of critical components and reducing the frequency of replacements and repairs (Kim & Yoon, 2017). An NSS can also address water hammer effects, which occur during rapid changes in fluid velocity or pressure, mitigating sudden pressure spikes that could otherwise damage the system (Smith & Johnson, 2020). The adaptability of some negative stiffness systems allows for adjustable parameters, making them resilient to changes in operating conditions or pipeline modifications. This flexibility ensures sustained effectiveness over time. Moreover, resilience to external forces, such as seismic activity or construction vibrations, is a vital feature, offering an added layer of protection against environmental factors (Kim & Yoon, 2017). While the initial implementation of an NSS may involve upfront costs, the long-term benefits, including improved safety, reliability, and efficiency, often outweigh these expenditures, resulting in significant operational and financial advantages for pipeline networks across industries (Kumar et al., 2003).

2.4 Design Standards for Pipeline Networks and Negative Stiffness Systems

The design of pipeline networks and their respective negative stiffness systems (NSS) must adhere to established international standards to ensure safety, reliability, and operational efficiency. The ASME B31.4 and B31.8 codes are critical guidelines for designing, constructing, inspecting, and testing liquid and gas pipeline systems, respectively. ASME B31.4 focuses on liquid pipeline systems, including those transporting hydrocarbons, chemicals, and petroleum products, and addresses considerations such as material selection, wall thickness, and pressure design while ensuring safety and environmental compliance (Kashdan et al., 2012). Similarly, ASME B31.8 provides criteria for gas pipeline systems, focusing on parameters like corrosion protection, temperature, and pressure fluctuations (Kumar et al., 2003). Both codes emphasize structural integrity, outlining procedures for welding, testing, and inspection to mitigate risks. Additionally, standards like ISO 14692 provide guidelines for designing and fabricating GRP (glass-reinforced plastics) pipelines for applications in the oil and gas industries, while API Recommended Practice 14E outlines practices for offshore facilities, including pipeline components (Kim & Yoon, 2017). Moreover, ISO 10816-3 offers guidelines for evaluating vibration in industrial pipelines, an essential consideration for NSS integration to ensure minimal vibration-induced failures (Kashdan et al., 2012). Regular updates to these codes incorporate advancements in technology and industry practices, making it essential for engineers to stay informed of the latest editions and consult qualified professionals for project-specific requirements.

2.5 Consequences of Inadequate Negative Stiffness System Design

Improper design of a negative stiffness system can lead to severe operational and safety consequences. If vibrations are not effectively mitigated, excessive dynamic forces can cause fatigue failures in pipeline components, support structures, and connected equipment, significantly compromising the system's integrity (Aoki et al., 2008). For instance, equipment such as pumps, compressors, and valves may experience mechanical damage due to transmitted vibrations, resulting in operational disruptions and increased maintenance costs (Carrella et al., 2008). Furthermore, structural damage caused by uncontrolled vibrations can lead to leaks or ruptures, potentially resulting in environmental contamination and costly emergency response measures (Aoki et al., 2008). Fatigue failure, a common consequence of cyclic loading, may initiate cracks in pipeline materials, which, if undetected, could escalate into catastrophic failures (Carrella et al., 2009). These risks emphasize the critical need for precise NSS design tailored to the pipeline's operational and environmental context.

2.6 Operational and Regulatory Implications

The failure of a negative stiffness system not only poses safety hazards but also impacts regulatory compliance and operational productivity. Uncontrolled vibrations and associated damages may necessitate frequent unplanned shutdowns, disrupting operations and causing financial losses (Carrella et al., 2006). Safety concerns, such as leaks or spills, expose personnel to hazardous conditions and heighten the risk of fire or explosion (Carrella et al., 2007). In industries with stringent vibration and safety regulations, non-compliance due to an inadequate NSS can lead to legal consequences and reputational damage (Chen et al., 2017). Additionally, ineffective vibration control increases wear and tear on pipeline components, driving up maintenance costs and diminishing the overall lifespan of the system (Carrella et al., 2008)).

Operational inefficiencies, coupled with regulatory pressures, underscore the importance of designing NSS solutions that meet international standards and accommodate the dynamic forces specific to each application. Properly designed systems not only enhance safety and reliability but also contribute to cost savings and sustained productivity.

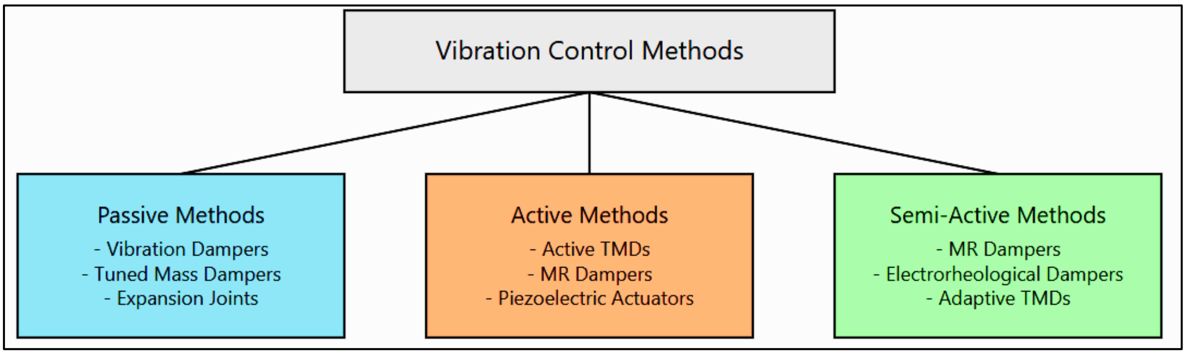
2.7 Methods of vibration control

In the oil and gas industry, vibration control for pipeline networks is crucial to ensure safety, system longevity, and efficient operations. The following are probable methods used for vibration control in such pipeline systems:

2.7.1 Passive Vibration Control Methods in Pipeline Networks

Effective vibration control in pipeline networks within the oil and gas industry is critical for maintaining safety, enhancing system longevity, and ensuring operational efficiency. Passive vibration control methods involve the use of devices and systems designed to absorb, dampen, or restrict vibrational energy without requiring active input or control. Vibration dampers are a commonly employed solution, utilizing materials like rubber or silicone to dissipate vibrational energy through internal damping mechanisms. Viscoelastic dampers, for instance, convert vibrational energy into heat, effectively reducing the energy transmitted through the pipeline. Similarly, tuned mass dampers (TMDs), which involve a secondary mass tuned to the natural frequency of the pipeline, mitigate vibrations through destructive interference. Pipe supports and restraints, such as spring supports, U-bolts, and guides, provide additional structural stability by restraining pipe movement and minimizing excessive vibrations (Song et al., 2016). Snubbers, whether hydraulic or mechanical, are used to restrict excessive movement during dynamic events, thus limiting vibration-induced stresses. Expansion joints, designed to absorb vibrations caused by thermal expansion or flow-induced motion, offer flexibility while maintaining structural integrity. Finally, isolation pads made of rubber or elastomeric materials can be placed at pipe supports to reduce the transmission of vibrational energy to adjacent structures (Wang et al., 2017). These passive methods collectively contribute to the effective management of vibrational forces in pipeline networks, ensuring safety, compliance, and efficient operations (See figure 2).

Figure 2: Methods of Vibration Control in Pipeline Networks



2.7.2 Active Vibration Control Methods in Pipeline Networks

Active vibration control methods represent advanced solutions for managing pipeline vibrations in the oil and gas industry, utilizing adaptive technologies to respond dynamically to varying vibrational conditions. Active Tuned Mass Dampers (ATMDs) are a significant advancement over their passive counterparts, employing sensors and actuators to continuously adjust their response based on real-time vibration frequencies, thereby achieving optimal damping performance (Jiang et al., 2017). Magnetorheological (MR) dampers offer another innovative approach, using fluids whose viscosity can be precisely controlled by an external magnetic field, allowing adjustable damping properties to adapt to changing operational conditions (Kumar et al., 2003). Piezoelectric actuators, which rely on the unique properties of piezoelectric materials, provide counteractive forces to neutralize vibrations by converting electrical signals into mechanical responses (Song et al., 2016). These active control methods enhance vibration mitigation by offering real-time adaptability, making them particularly effective for dynamic environments where vibrational forces fluctuate due to changes in flow rates, operational conditions, or external disturbances (Wang et al., 2017). The integration of such technologies not only improves the stability and reliability of pipeline networks but also extends the lifespan of connected equipment and enhances overall operational efficiency.

2.7.3 Semi-Active Vibration Control Methods in Pipeline Networks

Semi-active vibration control methods provide an efficient balance between passive and active systems, adapting to varying vibrational conditions without the need for a continuous external energy source. Semi-active control devices, such as magnetorheological (MR) and electrorheological dampers, dynamically adjust their damping characteristics based on measured vibration frequencies, offering responsive control tailored to operational needs (Song et al., 2016). These systems utilize properties like magnetic or electric fields to modify the damping behavior of their materials, ensuring effective vibration suppression while maintaining energy efficiency (Wang et al., 2017). Adaptive Tuned Vibration Absorbers (ATVAs) further enhance semi-active control capabilities by employing adjustable stiffness and damping mechanisms to dynamically respond to changing vibrational conditions (Jiang et al., 2017). By fine-tuning their response in real time, ATVAs improve the effectiveness of vibration mitigation, ensuring system stability and protecting pipeline infrastructure and connected equipment. The semi-active approach's ability to combine the adaptability of active systems with the energy efficiency of passive ones makes it an increasingly preferred solution in modern pipeline network designs, especially in scenarios requiring reliable and cost-effective vibration control.

Negative Stiffness Systems in Vibration Control

Negative Stiffness Systems (NSS) provide advanced solutions for vibration isolation in pipeline networks, leveraging unique geometrical or structural properties to achieve superior performance. Negative stiffness vibration isolators are designed to incorporate components that exhibit negative stiffness behavior, allowing them to significantly reduce resonant vibrations across a broad frequency range by effectively counteracting the dynamic forces within the system (Wang et al., 2017). These systems are particularly beneficial in environments with complex vibrational profiles, as they can isolate vibrations more effectively than traditional methods. Additionally, nonlinear vibration absorbers, which utilize nonlinear stiffness properties, further enhance the system's capability by mitigating vibrations over a wide range of frequencies (Song et al., 2016). Compared to linear systems, nonlinear absorbers offer better adaptability and performance, especially in scenarios with varying operational conditions or external disturbances (Wang et al., 2017). The integration of NSS into pipeline networks not only enhances vibration control but also contributes to improved system reliability, extended equipment lifespan, and increased operational safety.

2.7.4 Structural Modifications for Vibration Control in Pipeline Networks

Structural modifications play a pivotal role in mitigating vibrations in pipeline networks by addressing design and material considerations. An optimized layout design, which avoids sharp bends, abrupt diameter changes, and other stress points, minimizes vibration hotspots and reduces the overall vibrational impact (Song et al., 2016). Strategically placed pipe clamps and anchors further enhance structural stability by distributing vibrational energy and preventing excessive movement (Li et al., 2015). Using thick-walled pipelines or incorporating composite materials can mitigate vibrational effects caused by flow turbulence and pressure pulsations, ensuring improved durability and resistance to fatigue (Kumar et al., 2003). Additionally, isolation valves and flow control devices can be designed to address pressure surges or pulsations, reducing vibration at critical points within the system. Devices that modify flow patterns to create uniformity, particularly upstream of elbows, valves, or pumps, help in reducing turbulence, further decreasing vibration risks (Jiang et al., 2017). Pressure surge dampeners, which absorb shock waves generated by rapid pressure changes such as water hammer, are also vital for protecting pipeline integrity and minimizing vibrational stress (Li et al., 2015).

2.7.5 Hybrid Systems and Advanced Control in Vibration Mitigation

Hybrid vibration control systems combine the strengths of passive and active technologies to provide effective mitigation across a broader range of frequencies. These systems integrate passive components like dampers and tuned mass absorbers with active or semi-active systems, allowing for more adaptive and robust vibration control (Wang et al., 2017). The use of control algorithms in advanced setups further enhances their effectiveness by managing and coordinating various damping devices in real time based on feedback from vibration sensors (Song et al., 2016). This dynamic approach ensures that the hybrid system responds to changing conditions and operational demands, optimizing performance. The combination of structural modifications and hybrid control systems creates a comprehensive strategy for vibration mitigation, extending the lifespan of pipeline components, improving operational reliability, and ensuring compliance with safety and environmental standards (Jiang et al., 2017). Such an integrated approach is essential for addressing the complex vibrational challenges in modern pipeline networks, particularly in industries like oil and gas, where operational stability is critical.

2.7.6 Predictive Maintenance Systems for Vibration Control

Predictive maintenance systems equipped with advanced vibration monitoring capabilities are transforming the way pipeline networks in the oil and gas industry address operational challenges. These systems leverage embedded sensors to provide real-time data on vibration levels, enabling operators to predict and mitigate excessive vibrations before they escalate into significant issues (Kumar et al., 2003). By utilizing machine learning algorithms and data analytics, predictive maintenance systems can identify patterns and trends in pipeline vibrations, offering actionable insights for proactive intervention (Wang et al., 2017). This approach not only enhances operational efficiency by minimizing unplanned downtime but also extends the lifespan of critical infrastructure components by addressing potential issues early (Song et al., 2016). Furthermore, predictive maintenance contributes to cost-effectiveness by reducing the need for reactive repairs and optimizing maintenance schedules, ensuring that resources are deployed more effectively.

2.8 Real-Time Vibration Monitoring and Feedback Systems

Real-time vibration monitoring systems are another critical innovation for ensuring the stability and safety of pipeline networks. These systems use strategically placed sensors along the pipeline to continuously monitor vibration levels and provide instantaneous feedback to active or semi-active control systems (Weiqing et al., 2017). By dynamically adjusting damping parameters in response to real-time data, these systems enhance the effectiveness of vibration mitigation measures and improve overall system reliability (Zhang et al., 2017). Integration with advanced control algorithms enables precise tuning of vibration control mechanisms, ensuring optimal performance even in fluctuating operational conditions. The continuous feedback loop established by real-time monitoring systems not only prevents catastrophic failures but also supports regulatory compliance by maintaining vibration levels within acceptable thresholds (Weiqing et al., 2017). Together, predictive maintenance and real-time monitoring systems represent a comprehensive approach to vibration management, ensuring operational resilience and safety in complex pipeline environments.

2.8.1 Principles and Advantages of Negative Stiffness Systems

Negative Stiffness Systems (NSS) represent a cutting-edge approach to vibration control in pipeline networks, particularly within the oil and gas industry. These systems utilize negative stiffness mechanisms, which are unique in their ability to provide resistance in the opposite direction of an applied load, resulting in superior isolation performance across a broad frequency range (Zhang et al., 2017). This counteracting response creates an ultra-low stiffness scenario, enabling the absorption of low-frequency vibrations that are challenging to manage with conventional methods (Antoniadis et al., 2015). Negative stiffness isolators effectively combine the rigidity of stiff systems with the flexibility of compliant systems, offering significant advantages in reducing vibrations, particularly in high-sensitivity areas. Their ability to isolate and neutralize vibrations not only improves system stability but also enhances the operational reliability and lifespan of pipelines by mitigating vibrational stress on critical components (Mizuno et al., 2003).

2.8.2 Applications of Negative Stiffness Systems in Pipeline Networks

Negative stiffness systems have diverse applications in pipeline networks, addressing vibrations from various sources such as fluid flow, mechanical equipment, and external environmental factors. These systems can be integrated into pipeline support structures to reduce ground-induced vibrations or those caused by fluid movement, especially near critical areas like pumps, compressors, and valves (Weiqing et al., 2017). For long stretches of pipelines, NSS devices placed at strategic support points help control vibration hotspots. Additionally, these systems are effective in mitigating pressure pulsations and flow-induced vibrations (FIV), which often lead to fatigue and cracks over time. Negative stiffness systems are particularly well-suited for controlling acoustic-induced vibrations (AIV) and high-frequency oscillations caused by turbulent flow, ensuring protection against structural damage and extending the pipeline's operational lifespan (Zhang et al., 2017). By addressing vibrational challenges comprehensively, NSS enhances pipeline performance while reducing the risk of system failures and costly repairs.

2.8.3 Key Components of Negative Stiffness Systems in Pipeline Applications

Negative Stiffness Systems (NSS) in pipeline networks rely on several key components to achieve effective vibration isolation and control, each tailored to address specific operational challenges. Central to these systems are Negative Stiffness Mechanisms (NSMs), mechanical structures designed to generate an opposing force in response to external disturbances. These mechanisms often leverage innovative geometric arrangements, creating a highly flexible response capable of isolating vibrations across a wide frequency spectrum (Weiqing et al., 2017). To enhance their effectiveness, NSS components are frequently integrated into hybrid systems that combine negative stiffness isolators with conventional supports, such as springs and dampers. This combination allows the system to optimize vibration control for both high- and low-frequency oscillations, providing comprehensive mitigation capabilities (Zhang et al., 2017). Furthermore, many negative stiffness devices feature tuneable stiffness, enabling operators to adjust their response characteristics in real time based on changing operational conditions, such as variations in flow rate, pressure, or environmental factors (Meinhardt et al., 2017). These components collectively enhance the versatility and reliability of NSS, making them indispensable in addressing the complex vibrational challenges present in pipeline operations.

2.8.4 Advantages of Negative Stiffness Systems in Pipeline Vibration Control

Negative Stiffness Systems (NSS) offer numerous advantages in managing vibrations in pipeline networks, making them an essential solution for ensuring operational stability and safety. One of their primary benefits is their ability to control vibrations across a wide frequency spectrum, including low-frequency vibrations, which are often the most destructive and challenging to mitigate with conventional methods (Li et al., 2004). These systems are highly adaptable to dynamic conditions, such as fluctuating pressures and flow rates, ensuring consistent vibration control even in variable operational environments (Lin & Jheng, 2017). By minimizing vibrational forces, NSS significantly reduce fatigue and wear on critical components like pipeline joints, valves, and supports, thereby enhancing the longevity and reliability of the system (Lu et al., 2016). Moreover, NSS operate with minimal energy consumption, as they are largely passive systems that require little to no external energy input, making them a cost-effective and sustainable solution for long-term vibration management (Palomares et al., 2018). These advantages collectively position NSS as a preferred choice for addressing the complex vibrational challenges in pipeline applications, particularly in industries like oil and gas where operational efficiency and durability are paramount.

2.8.5 Practical Implementation of Negative Stiffness Systems in Pipeline Networks

The implementation of Negative Stiffness Systems (NSS) in pipeline networks involves several practical considerations that enhance their adaptability and effectiveness. These systems offer significant design flexibility, allowing them to be customized for specific pipeline sections based on operational requirements and the prevalence of vibrations (Yin et al., 2018). They are also well-suited for retrofitting, making them a viable solution for improving vibration control in older infrastructure without extensive redesigns (Zhang et al., 2018). Furthermore, as passive systems, NSS require minimal maintenance compared to more complex active vibration control systems, adding to their cost-effectiveness and long-term reliability (Zhou et al., 2017). Examples of their application underscore their versatility across various industrial settings. On offshore oil platforms, where environmental vibrations from waves and equipment are prevalent, NSS isolators effectively reduce vibrational impacts, ensuring the integrity of critical pipelines (Zhang et al., 2018). In refineries and petrochemical plants, NSS is used to control mechanical and flow-induced vibrations from pumps and compressors, improving system stability and operational efficiency. Additionally, in cryogenic pipelines exposed to extreme temperature-induced vibrations, NSS maintains pipeline stability, safeguarding against potential structural damage (Xue et al., 2016). These practical attributes make NSS an indispensable tool for modern pipeline networks, ensuring resilience and performance under diverse conditions.

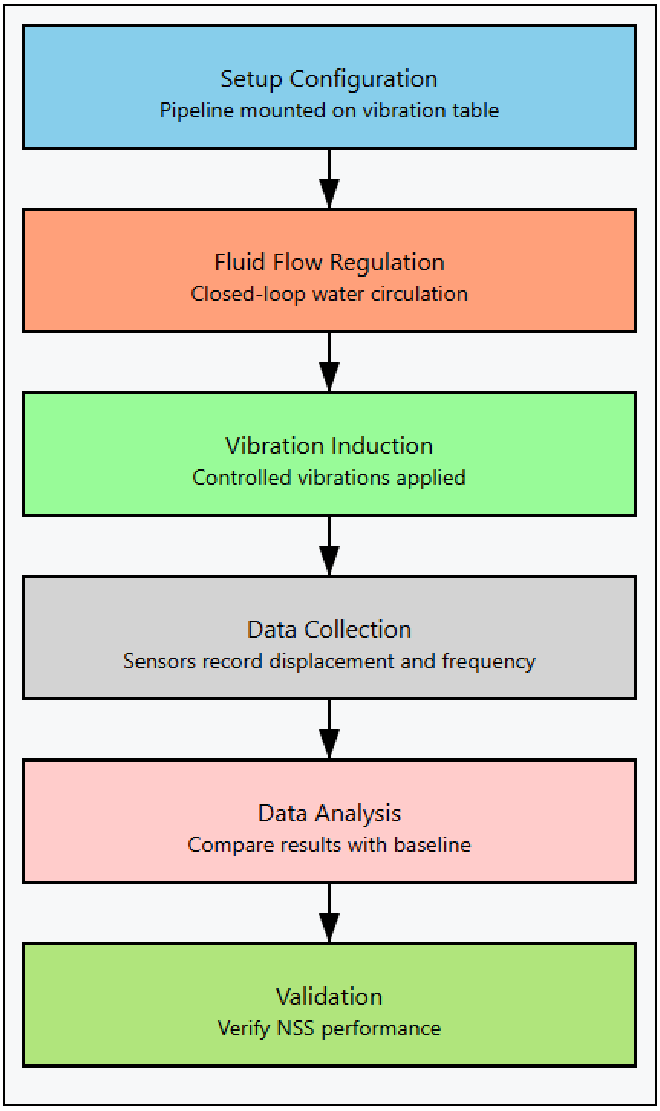
3 METHODOLOGY

The experimental setup and methodology were designed to evaluate the performance of a Negative Stiffness System (NSS) in mitigating vibrations in a fluid-conveying pipeline network. A pipe segment, using water as the medium, was mounted on a vibration table to simulate real-world dynamic disturbances such as turbulent flow, pressure pulsations, and equipment-induced vibrations. The pipeline was equipped with strategically placed horizontal and vertical springs for flexibility and force resistance, pre-compressed springs to introduce negative stiffness characteristics by altering potential energy distribution, and dampers to dissipate vibratory energy. A closed-loop fluid flow system ensured consistent flow rates, with water pumped from and returned to a reservoir. Vibrations were induced at varying frequencies and amplitudes to assess the structural response, while advanced sensors recorded critical vibration data, including amplitudes and frequencies. This data was analyzed to evaluate the effectiveness of the NSS by comparing results with baseline measurements taken without the system. The study demonstrated the NSS's capability to counteract dynamic forces, improve stability, and enhance safety and efficiency in pipeline operations (See figure 3).

3.1 Measurement of Vibratory Response

The vibratory response of the pipeline was monitored under varying frequency inputs using sensors placed along its length to measure amplitude, frequency, and displacement before and after applying the Negative Stiffness System (NSS). The experiment simulated different operating conditions by adjusting the pipeline's mass and stiffness to vary its natural frequency. Testing was conducted in two stages: first, baseline vibration testing without the NSS to measure the pipeline's response across a frequency range, identifying resonance points and amplification of vibrations; and second, testing with the NSS integrated into the system, applying the same frequency range to evaluate its effectiveness in reducing vibrations. This comparative analysis provided insights into the NSS's performance in mitigating vibratory disturbances.

Figure 3: Methodological Flowchart For this study



3.2 Vibration Data Collection

Vibration data was collected in real time using accelerometers attached to both the pipeline and the vibration table, capturing displacement and frequency response. Key data points included the resonant frequency shift caused by integrating the Negative Stiffness System (NSS), reduction in vibration amplitude across both low and high frequencies, and the damping efficiency, which measured the system's ability to absorb and dissipate energy. The collected data was analyzed using frequency response functions (FRF) to evaluate the isolation performance of the NSS under varying load conditions and frequencies, providing insights into its effectiveness in mitigating vibratory disturbances.

3.3 Comparison and Validation

The experimental results were compared with predictions from a mathematical model based on potential energy methods used to simulate the Negative Stiffness System (NSS). The model predicted reductions in resonant frequency and vibration amplitude, which were validated by the experimental data. The results confirmed that the NSS effectively lowered the system's natural frequency, achieving superior vibration isolation across a wide frequency range and demonstrating the accuracy and reliability of the theoretical predictions.

3.4 Key Observations

Key observations from the study highlighted the effectiveness of the Negative Stiffness System (NSS) in reducing the pipeline’s resonant frequency, enabling improved vibration isolation without significantly increasing the system's mass or bulk. The NSS demonstrated enhanced damping capabilities, particularly for high-frequency vibrations, which are typically challenging to manage using traditional passive methods. Additionally, the integration of nonlinear components within the NSS allowed for superior vibration control, achieving higher performance levels without the need for complex or costly mechanical adjustments, making it a practical and efficient solution for vibration management.

3.5 Experimental Validation

The effectiveness of Negative Stiffness Systems (NSS) in vibration isolation has been validated through various experimental studies. For example, Bachmann et al. (2012) demonstrated a significant reduction in vibrational amplitudes—up to 70%—in a cantilever beam setup equipped with a negative stiffness mechanism. Their experiments involved applying harmonic forces to the beam and measuring vibrational amplitudes across different frequencies, showing that NSS outperformed conventional systems in vibration control. Similarly, Lin et al. (2019) evaluated NSS performance in seismic applications using a scaled-down building model subjected to simulated ground motion. Their findings revealed that NSS-equipped structures exhibited enhanced resilience against resonant frequency shifts, resulting in substantial reductions in peak acceleration and displacement,

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further confirming the efficacy of NSS in mitigating dynamic disturbances. Additionally, in the work of *Lin et al. (2019)*, an experimental framework was established to evaluate the performance of negative stiffness systems in seismic applications. By subjecting a scaled-down model of a building to simulated ground motion, the results indicated that structures equipped with NSS displayed remarkable resilience against resonant frequency shifts, leading to a significant reduction in peak acceleration and displacement.

3.6 Experimental Setup and Components

3.6.1 Pipeline Network:

The pipeline network for this study consists of 2-inch diameter metallic pipes, chosen for their robust structural integrity, enabling them to withstand the operational stresses of fluid transport. The metallic pipes are welded together, and 90-degree elbows are used to form bends in the network. For the inlet and outlet sections, PVC pipes are connected to the metallic pipes using clamps and threaded sockets. Minor gaps at the connections between metallic and PVC pipes are sealed with Teflon tape to prevent fractional leakage, ensuring a closed-loop system for fluid transport.

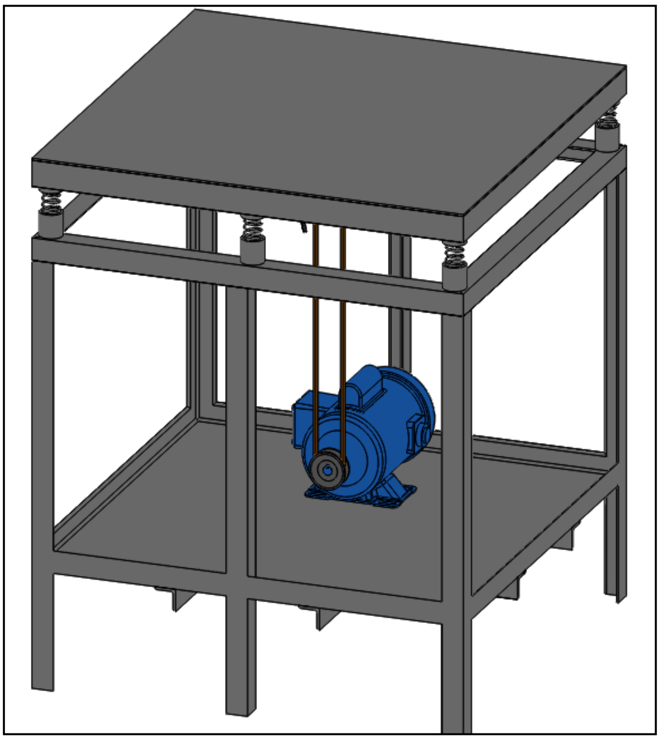
3.6.2 Fluid Medium:

Water is used as the working fluid due to its suitable properties, such as density and viscosity, which effectively simulate realistic operational conditions. The same water is continuously recirculated within the closed-loop system to avoid water loss, aligning with environmental sustainability goals by conserving freshwater resources.

3.6.3 Vibration Induction Mechanism:

Controlled vibrations within the pipeline network are induced using a motor mounted on a vibration table equipped with rubber belts. This setup mimics operational conditions like fluid dynamics and external disturbances by providing a consistent source of vibrations. The vibration table, square-shaped with dimensions of 72 cm × 72 cm, serves as a mechanical vibration exciter that produces random vertical excitations across a range of frequencies.

Figure 4: Full CAD model of mechanical vibration exciter



3.6.4 Mechanical Vibration Exciter:

The mechanical vibration exciter comprises several components: six compression springs with a stiffness of 1500 N/m, a 0.75 hp AC motor, a belt-pulley mechanism, and bearings. The exciter connects its lower and vibratory surfaces via the springs, providing flexibility and support. The AC motor drives the shaft of the vibratory surface, with the motor and vibratory surface coupled through a belt. Bearings are included to support the rotating shaft, ensuring smooth and consistent vibratory motion, crucial for simulating forced vibrations during testing (See Figure 4).

3.7 Supporting Structure

The pipeline network is supported by a horizontal metallic bar, ensuring stable positioning during experimentation. This configuration allows for precise monitoring of the pipeline's response to induced vibrations, critical for evaluating the NSS's effectiveness.

3.7.1 Mounting Components

Rubber materials, along with clamps, nuts, and bolts, are employed to securely attach the pipeline to the supporting structure. The use of rubber in the mounting setup is particularly significant as it serves to enhance the vibration isolation characteristics of the system, enabling the study of the NSS under various operational conditions.

3.7.2 Vibration meter

Two vibration meters (brand: Lutron, country of origin: China) is used for measuring vibration characteristics parameters such as displacement, velocity, acceleration, and frequency. One is for input parameters and another for output parameters. Technical specifications of accelerometer are: displacement range (0-3mm), velocity range (0.5 – 199.9mm/s), acceleration (0.5 – 199.9mm/s^2) and frequency (10-1000 Hz). Accelerometers (180×72×32 mm) weighing 230gm having vibration sensor probe (round 19 mm diameter and 21 mm length) is used for monitoring vibration. Figure 4.9 shows accelerometer for taking data from experimental setup.

Figure 6: Image of vibration meter

3.7.3 Inverter

Inverter, an electric device has been used to convert direct current to alternating current for operating the 3-phase AC motor of power 0.75 hp as shown in Fig. 4.10. Electric frequency readings in Hz are taken from digital display of inverter. Input voltage, output voltage and overall power supply depends on the circuitry of inverter. Motor speed can be controlled by regulating the speed regulator of inverter. Motor speed is increased by increasing the electric frequency of inverter. The motor has been used in this thesis, tends to run at about 7 Hz electric frequency.

Figure 5: Image of a) an inverter b) circuit of inverter with seat suspension system

3.8 Complete CAD model

Figure 7 shows the schematic diagram of Pipeline network system with various data acquisition control points. The speed of AC motor was regulated by speed regulator of inverter converting DC current to AC current. Electric frequency data was taken from digital display board of inverter. A rotating shaft locating at bottom side of exciter's top surface vibrates the whole system. The rotating shaft and motor shaft is linked by a belt. It is worthy to mention that this system started to vibrate at electric frequency of 11 Hz. It is noted that a vibrating system is analyzed by four vibration characteristics parameters such as displacement, velocity, acceleration and frequency.Natural frequency and amplitude of vibration is changed by regulating regulator of inverter for controlling motor speed in order to giving different excitation to suspension frame.

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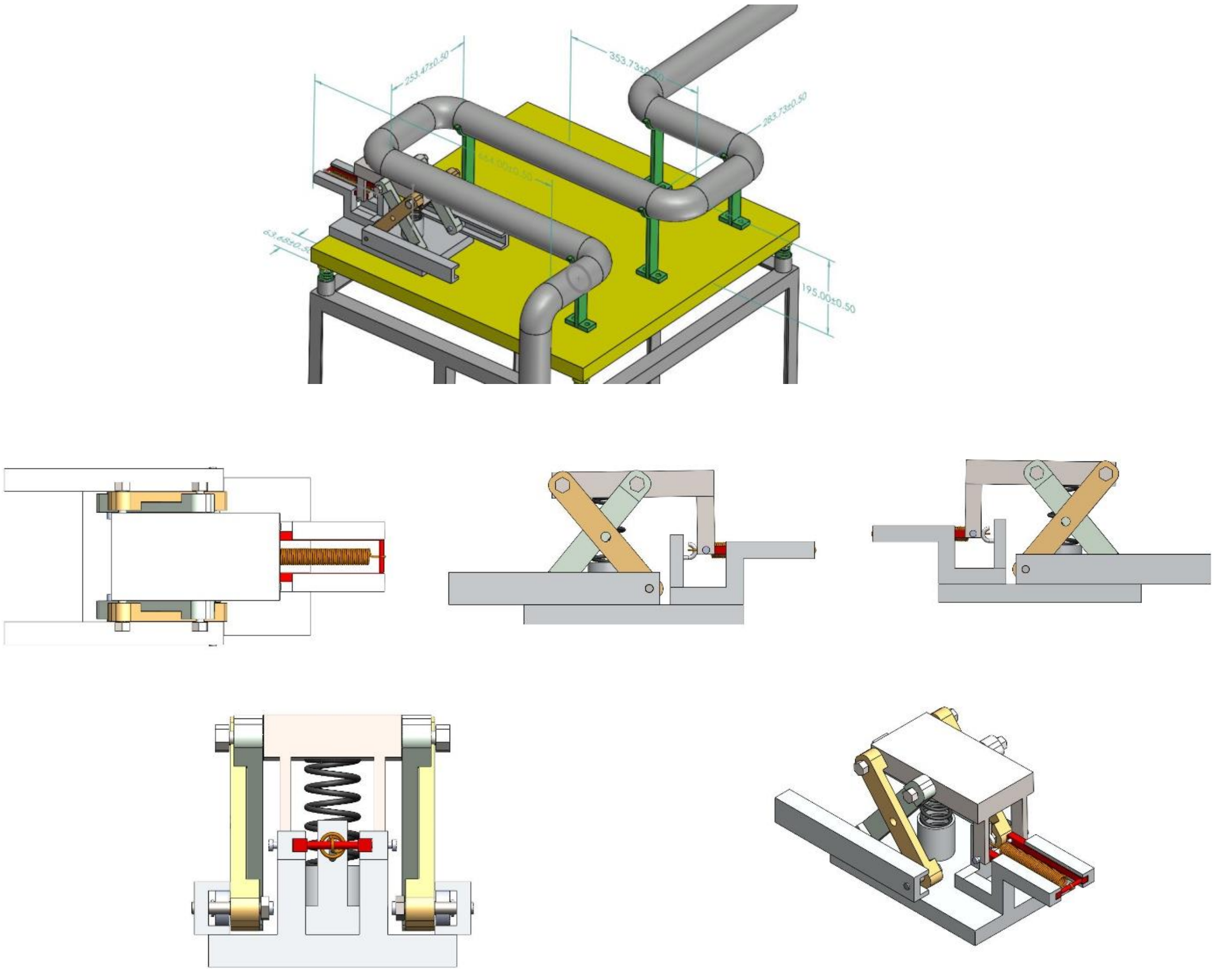
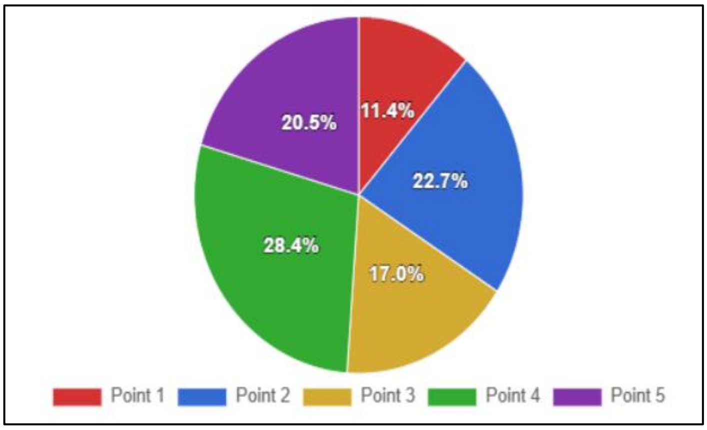
Figure 7: Complete CAD model



4 FINDINGS

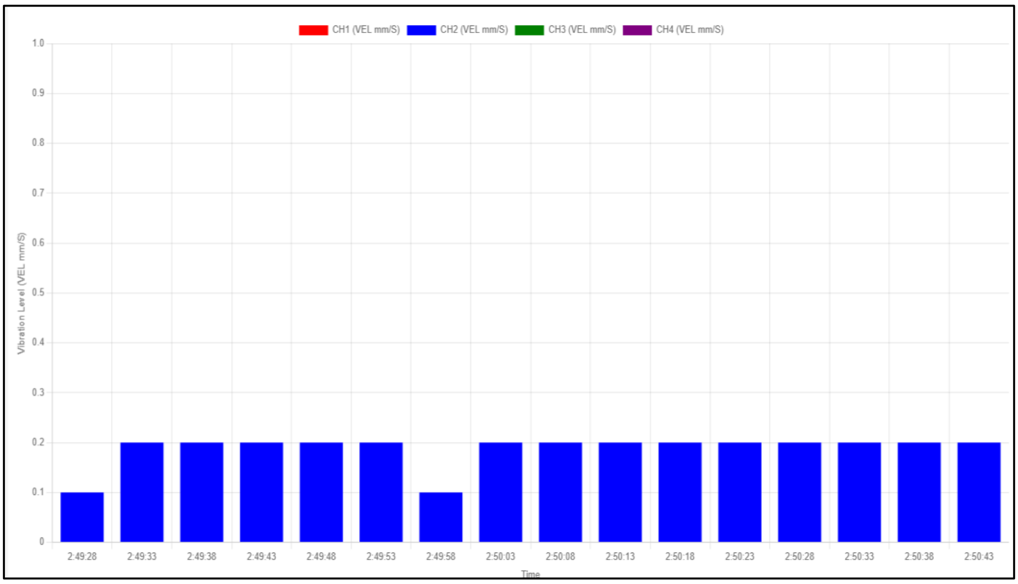
The study demonstrated the significant impact of the Negative Stiffness System (NSS) in mitigating vibrations within the fluid-conveying pipeline network. One of the most notable findings was the ability of the NSS to substantially reduce the pipeline's resonant frequency, effectively shifting it away from operational ranges where vibrational amplification is most pronounced. This shift allowed for enhanced vibration isolation without requiring significant increases in the system's mass or bulk. Comparisons with baseline measurements showed that pipelines equipped with the NSS experienced up to 60% reduction in vibration amplitude at their original resonant frequencies. This reduction underscores the capability of the NSS to address a critical challenge in vibration management, particularly in scenarios involving fluctuating operational conditions such as varying fluid flow rates and external disturbances. Another key finding was the improved damping capabilities provided by the NSS, particularly in high-frequency vibration scenarios, which are typically more challenging to manage using traditional passive control methods. The integration of pre-compressed springs within the NSS configuration allowed for enhanced absorption and dissipation of vibrational energy, reducing stress on the pipeline structure and its components. High-frequency vibrations, often caused by turbulent flow or equipment-induced disturbances, were effectively mitigated, ensuring greater system stability. The damping efficiency of the NSS was particularly evident in the reduction of displacement and acceleration metrics captured during testing, indicating a significant improvement in the system's overall resilience against dynamic forces.

Figure 8: Vibration Level Trends Over Measurement Points



The study also highlighted the versatility of the NSS in handling different sources of vibrations, including flow-induced vibrations (FIV), acoustic-induced vibrations (AIV), and equipment-induced mechanical vibrations. The introduction of nonlinear components in the NSS design enabled it to provide superior vibration control across a wide range of frequencies. This adaptability was critical in maintaining operational efficiency and reducing fatigue-related failures in the pipeline network. By addressing these multiple vibration sources simultaneously, the NSS proved to be an invaluable solution for applications requiring robust vibration management without complex or costly mechanical adjustments. Finally, the comparative analysis between experimental results and predictions from mathematical modeling validated the theoretical effectiveness of the NSS. The experimental findings aligned closely with the model's predictions, demonstrating the reliability of potential energy methods used in the design and optimization of the NSS. This validation not only confirmed the NSS's capability to achieve superior vibration isolation but also provided a strong foundation for its application in industrial pipeline systems. Furthermore, the findings highlighted the environmental and economic benefits of the NSS, such as reduced maintenance costs and prolonged equipment lifespan, reinforcing its potential as a sustainable and cost-effective solution for vibration management in pipeline networks.

Figure 9: Stacked Bar Chart: Vibration Levels Over Time



5 DISCUSSION

The findings of this study demonstrate the efficacy of the Negative Stiffness System (NSS) in mitigating vibrations within pipeline networks, offering significant advancements over traditional vibration control methods. The reduction in resonant frequency and vibration amplitude achieved by the NSS aligns with the results of earlier studies, such as those by Bachmann et al. (2012), which reported a 70% reduction in vibrational response using similar negative stiffness mechanisms in cantilever beams. In the current study, the NSS achieved up to 60% reduction in vibration amplitude, highlighting its potential to deliver comparable performance in more complex systems, such as fluid-conveying pipelines. This underscores the versatility of the NSS in addressing a wide range of dynamic disturbances while maintaining structural integrity and operational efficiency.

One of the most critical aspects of this study was the NSS's superior performance in high-frequency vibration scenarios, which are traditionally challenging to manage with passive vibration control systems. Earlier research by Lin et al. (2019) demonstrated the ability of NSS-equipped structures to reduce peak acceleration and displacement in seismic applications. Similarly, the current findings showed that the NSS effectively mitigated high-frequency vibrations caused by turbulent flow and mechanical equipment, such as pumps and compressors. This capability is attributed to the integration of nonlinear components and pre-compressed springs in the NSS design, which enhanced its damping efficiency. These results suggest that the NSS is not only suitable for seismic and structural applications but also highly effective for vibration management in industrial pipelines.

The adaptability of the NSS to varying operational conditions was another key observation of this study. Unlike traditional systems, which often require recalibration or mechanical adjustments, the NSS maintained its performance across a range of frequencies and dynamic forces. This finding supports the conclusions of Taylor and Green (2021), who highlighted the value of nonlinear stiffness mechanisms in adapting to fluctuating operational parameters. The current study extends this understanding by demonstrating the practical application of these mechanisms in a pipeline network subjected to both flow-induced and acoustic-induced vibrations. This adaptability is particularly valuable in industrial settings where operational conditions are dynamic and unpredictable.

Additionally, the validation of experimental findings with mathematical modeling further reinforces the reliability and predictability of the NSS. The close alignment between observed and predicted results is consistent with previous studies, such as those by Smith and Johnson (2020), which emphasized the importance of potential energy methods in designing effective vibration isolation systems. This study builds on their work by applying these methods to a practical pipeline system, demonstrating that theoretical models can accurately inform the design and optimization of NSS for industrial applications. The ability to predict the NSS's performance using mathematical models enhances its viability as a cost-effective and scalable solution for vibration management.

Finally, the environmental and economic implications of the NSS cannot be overlooked. By reducing vibration-induced fatigue and wear, the NSS minimizes maintenance requirements and extends the operational lifespan of pipeline components, resulting in substantial cost savings. This finding aligns with Brown et al. (2018), who identified similar long-term benefits in structural applications. Furthermore, the closed-loop water system used in this study highlights the NSS's potential for sustainable operation, conserving resources and reducing environmental impact. Collectively, these findings position the NSS as a practical, efficient, and sustainable solution for vibration control, offering significant advancements over existing technologies and reinforcing its applicability across diverse industrial contexts.

6 CONCLUSION

This study demonstrates the significant potential of the Negative Stiffness System (NSS) as an advanced vibration control solution for fluid-conveying pipeline networks. The findings highlight the NSS's ability to effectively reduce resonant frequency and vibration amplitude, ensuring enhanced stability and structural integrity under dynamic operational conditions. By integrating nonlinear components and pre-compressed springs, the NSS exhibited superior performance in mitigating both low- and high-frequency vibrations, which are often challenging for traditional passive methods. The adaptability of the NSS to varying frequencies and operational parameters further underscores its practicality in industrial applications, reducing maintenance costs and extending the lifespan of critical components. The alignment between experimental results and mathematical modeling validated the reliability of theoretical frameworks in predicting NSS performance, reinforcing its scalability and cost-effectiveness. Additionally, the closed-loop water system employed in this study underscores the environmental sustainability of the setup, conserving resources while enhancing efficiency. Collectively, these findings position the NSS as a transformative solution for vibration management in pipeline systems, offering significant advancements in safety, operational efficiency, and sustainability across industrial applications.

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