Power System Technology
ISSN:1000-3673

Received: 16-10-2025 **Revised: 05-11-2025** **Accepted: 06-12-2025**

High-Cycle Fatigue Failure and Damping Solutions for Vibrating Process Piping in Gas Processing Plants: A Review and Industrial Case Study

Kamal Ahmed Aboelkamal Ali

Abstract

Vibration-induced fatigue remains one of the most persistent mechanical-integrity threats in gas-processing plants. Complex flow regimes, high-energy acoustic sources and flexible piping layouts combine to generate dynamic loads that can initiate and propagate fatigue cracks, often with limited or no prior visible damage. This paper has two objectives. First, it synthesizes recent research on flow-induced vibration (FIV), acoustic-induced vibration (AIV), and structural resonance in process piping, with emphasis on prediction, evaluation and mitigation in gas-processing systems. Second, it documents an industrial case study from a large onshore gas facility where capacity-increase testing revealed excessive vibration on 18″ raw-gas inlet lines at 430 MMSCFD, leading to a structured campaign of vibration measurements, mitigation design and re-assessment.

The literature review covers developments in FIV and AIV mechanisms, fatigue-life prediction methods, high-fidelity numerical modelling (including combined acoustic–structural and fluid–structure interaction models), and state-of-the-art mitigation technologies such as tuned mass dampers, vibro-impact systems, viscoelastic treatments and material hardening. While Energy Institute (EI) and ASME screening methods are valuable first-pass tools, they are shown to be insufficient for complex multiphase flows and transient operation without follow-up modal or transient analyses.

The industrial case study demonstrates how these principles were applied in practice. Vibration measurements on four process trains initially identified “concern area” or “concern line” conditions at dead-leg branches, small-bore connections and bypass bracing supports near an emergency shutdown valve. A dedicated pipe support, added mass, clamp re-tightening and a new pipe-to-pipe support on a MEG injection line were designed and implemented. Subsequent measurements at 430 MMSCFD showed up to ~70% reduction in resultant RMS velocity at the most critical branch, with all points falling within EI acceptance limits. A later survey on a fifth train (Train 6) confirmed acceptable behavior up to 420 MMSCFD, with only a few locations classified as “concern line” and targeted for ongoing optimization.

The results highlight the importance of early screening, targeted high-fidelity analysis, tailored damping and stiffening solutions, and continuous monitoring. An integrated, data-driven vibration-management framework is recommended to support safe throughput increases and long-term mechanical integrity of gas-processing piping systems.

Power System Technology
ISSN:1000-3673

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

Keywords: flow-induced vibration; acoustic-induced vibration; piping fatigue; gas-processing plants; tuned mass dampers; Energy Institute guidelines; dynamic mitigation; mechanical integrity.

1. Introduction

Vibration-induced fatigue is a long-recognized but still under-estimated integrity threat in gas-processing facilities. Process piping in these plants is exposed to high gas velocities, abrupt pressure changes, multiphase flow, and frequent transients. These conditions can produce dynamic loading that drives high-cycle fatigue, often at localized stress raisers such as small-bore branches, fillet welds, supports and dead-legs.

Unlike corrosion or low-cycle fatigue, vibration-induced failures can occur with little visible warning. Small cracks may propagate rapidly once a resonance condition is activated, leading to sudden leakage or rupture. At the same time, early symptoms—such as slightly elevated vibration levels, audible noise or loose supports—are easy to overlook during routine operation.

Field experience and documented incidents show that both FIV, driven by fluid turbulence and vortex shedding, and AIV, driven by high-frequency acoustic waves from pressure-reducing devices, have caused failures in transmission pipelines, gas terminals and processing plants (e.g. Matta & Szasz, 2018; Ridens et al., 2018).

Although the mechanisms are well known and industry guidelines such as the Energy Institute (EI) "Guidelines for the Avoidance of Vibration Induced Fatigue in Process Pipework" are widely used, modern plants still experience vibration problems. Increased throughput targets, compact layouts, lighter piping designs and complex multiphase operation all reduce the margin between safe and problematic dynamic behavior (Pontaza, 2021; Antaki, 2023). Small-bore connections (SBCs), in particular, are frequently found to fail in high-cycle fatigue due to their low stiffness and high local stress concentration (Cheong, 2024).

High-Cycle Fatigue Failure Anal…

In parallel, numerical modelling capabilities have advanced considerably. Combined acoustic–structural finite element analysis (FEA), fluid–structure interaction (FSI) simulations and hybrid frequency-domain screening approaches can now be applied to complex piping systems (Coulon et al., 2018; Lin et al., 2025; Aloschi et al., 2023). These models significantly improve prediction of dynamic stresses and fatigue life but require high-quality input data, expert interpretation and computational effort, which may limit their routine application.

Against this backdrop, the present work combines two elements:

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

1. A narrative–systematic review of research from approximately 2012–2025 on vibration-induced fatigue in gas-processing piping, focusing on mechanisms, assessment tools and mitigation strategies.
2. An industrial case study from the Zohr onshore gas plant, where a capacity-increase programme to 430 MMSCFD per train revealed excessive vibration on 18″ raw-gas inlet lines and triggered a structured mitigation and verification campaign.

   VIBRATION TECHNICAL ASSESSMENT …

By connecting state-of-the-art research with practical field experience, the paper aims to provide engineers and integrity specialists with a coherent framework for assessing and mitigating vibration-induced fatigue in similar installations.

2. Vibration-Induced Fatigue in Process Piping: Mechanisms and State of the Art

2.1. Flow-Induced Vibration (FIV)

Flow-induced vibration arises when the moving fluid exerts fluctuating forces on the pipe wall and internal fittings. The dominant excitation mechanisms in gas-processing conditions include:

- **Vortex shedding and turbulent buffeting** around tees, reducers and other discontinuities.
- **Multiphase slugging**, where alternating liquid slugs and gas pockets create large density and momentum variations.
- **Interaction with reciprocating equipment**, where pressure pulsations from pumps or compressors excite piping resonances.

  High-Cycle Fatigue Failure Analysis

Research shows that FIV-related fatigue failures tend to occur in unsupported spans and at geometric discontinuities such as elbows, small-bore branches and dead-legs (Haile, 2022; Ahmed et al., 2022). When the excitation frequency approaches a natural frequency of the piping span or branch, resonant amplification can drastically increase stress ranges even when overall vibration amplitudes are modest.

2.2. Acoustic-Induced Vibration (AIV) and High-Frequency Fatigue

AIV is driven by high-frequency acoustic pressure waves generated downstream of significant pressure-reducing devices such as control valves, orifice plates and blowdown nozzles. These acoustic waves can excite high-order shell modes of thin-walled piping, typically above 500 Hz, leading to very high local dynamic stresses at weld toes and other stress raisers (Ridens et al., 2018).

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

Compared with FIV, AIV can produce fatigue damage in a much shorter time, particularly at locations where geometry concentrates stress (tees, reducers, SBCs). Screening methods that estimate acoustic power based on pressure drop and downstream geometry are now standard, but several field failures have occurred where AIV risk was underestimated or operational conditions deviated from design assumptions (Moussa, 2013; Pontaza, 2021).

2.3. Numerical and Predictive Modelling

Contemporary modelling approaches have substantially improved the ability to predict vibration-induced fatigue:

- **Acoustic–structural FEA** couples acoustic loading to Structural FEA models to obtain stress fields and fatigue usage factors under high-frequency excitation, giving better AIV predictions than empirical screening alone (Coulon et al., 2018).

  High-Cycle Fatigue Failure Anal…
- **Fluid–structure interaction (FSI) models** combine CFD and structural dynamics to capture complex, nonlinear interactions between flow and structure, including tuned-mass-damper behavior and multiphase effects (Lin et al., 2025).

  High-Cycle Fatigue Failure Anal…
- **Hybrid screening and modal analyses** in the frequency domain allow early identification of potential resonance and AIV/FIV overlap before detailed models are built (Pontaza, 2021; Antaki, 2023; Emmerson, 2020).

These approaches consistently show good agreement with experimental data where validation is available, but their adoption in routine design is constrained by cost, modelling effort and data availability.

2.4. Mitigation Systems and Active Control

Historically, vibration mitigation relied on:

- Adding or relocating conventional supports and braces.
- Increasing wall thickness or changing layout to avoid known resonant spans.

Recent research, however, has focused on dynamic and adaptive mitigation devices:

- **Tuned mass dampers (TMDs) and pounding TMDs (PTMDs)** applied to suspended piping and SBCs have demonstrated substantial reductions in vibration amplitudes—often 50–70%—by adding targeted damping and detuning resonances (Tan et al., 2019; Cheong, 2024; Lin et al., 2025).
- **Vibro-impact systems** that exploit controlled internal impacts or gaps can dissipate energy efficiently in high-frequency AIV scenarios (Aloschi et al., 2023).

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

High-Cycle Fatigue Failure Anal…

- **Material-based solutions**, such as boronizing to harden steel surfaces, have been shown to improve fatigue resistance under acoustic loading (Saeed et al., 2021).

  High-Cycle Fatigue Failure Anal…

In practice, dynamic devices and material improvements are often more effective than purely structural stiffening, especially during retrofit, where large layout changes are impractical.

2.5. Industry Guidelines and Remaining Gaps

Industrial guidelines from the EI and ASME provide standardized screening procedures for both FIV and AIV. They are very effective for identifying high-risk acoustic sources and obviously flexible spans, and they enable consistent communication between design, operations and integrity teams (Antaki, 2023; Emmerson, 2020; Matta & Szasz, 2018).

However, several gaps remain:

- Most screening methods assume steady-state flow; they do not explicitly address severe transients such as blowdown, start-up or upset conditions.
- Multiphase slugging and rapidly changing flow regimes are difficult to represent accurately in simple formulas or single-phase CFD.

  High-Cycle Fatigue Failure Anal…

- Aging assets with incomplete design records, undocumented modifications and retrofitted supports can exhibit vibration modes that differ significantly from original assumptions (Al Sawwafi, 2022).
- Machine-learning-based diagnostics are emerging but not yet widely integrated into mechanical-integrity programs.

Overall, the literature emphasizes that robust vibration control demands an integrated approach combining early screening, targeted advanced analysis, fit-for-purpose mitigation and systematic monitoring.

3. Methodology

3.1. Literature Review Approach

A narrative–systematic review was adopted to synthesize research findings across four domains: vibration mechanisms, assessment tools, mitigation strategies and field case studies.

High-Cycle Fatigue Failure Analysis

Sources included peer-reviewed journal articles, ASME/OMAE conference papers and industry reports published roughly between 2012 and 2025. Studies were included if they:

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

- Analyzed FIV, AIV or structural resonance in industrial piping.
- Provided experimental or numerical data related to vibration or fatigue life.
- Proposed or evaluated mitigation technologies or screening methodologies.
- Reported field failures or retrofits linked to vibration.

High-Cycle Fatigue Failure Analysis

The selected references were coded according to mechanism (FIV, AIV, multiphase, mechanical), analysis method (screening, FEA, CFD-FSI), mitigation type (structural, dynamic device, materials) and whether they were experimental, numerical or field-based.

3.2. Industrial Data Sources

The case study draws on two internal technical documents from the Zohr onshore gas plant:

1. A **vibration technical assessment** for the raw gas train inlets during a capacity-increase campaign to 430 MMSCFD per train ("VIBRATION TECHNICAL ASSESSMENT RAW GAS LINES – TRAINS INLET – 430 MMSCFD").

   VIBRATION TECHNICAL ASSESSMENT …

2. A **condition-monitoring report** for the 18″ inlet gas line of **Train 6**, including measurement procedures and evaluation against EI criteria (report reference O-ZH-101-AIM-XCM-330-0002).

   TR6

The technical assessment includes detailed descriptions of the plant configuration, measurement positions, operating conditions and mitigation actions on Trains 1–4, plus attachments with vibration spectra. The Train-6 report provides operating points at 350, 400 and 420 MMSCFD and classification of measurement points as "accept" or "concern line" according to EI guidelines.

Both documents used tri-axial vibration measurements (two radial directions and one axial) taken with a CSI 2140 vibration analyzer, with evaluation based on RMS velocity and EI acceptance charts.

TR6

4. Industrial Case Study: 18″ Raw-Gas Train Inlet at Zohr Onshore Gas Plant

4.1. Plant and Capacity-Increase Context

The Zohr onshore processing plant comprises multiple gas-conditioning trains, each designed for an inlet capacity of 393 MMSCFD. A Capacity Increase Assessment (CIA) was launched

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

to determine whether existing facilities could safely operate at 110% and 120% of this design capacity, corresponding to about 430 and 470 MMSCFD per train.

VIBRATION TECHNICAL ASSESSMENT …

As part of this CIA, a field test campaign with support from DOW Chemical was conducted in October 2018 (Week 41). During the first test on **Train 2**, the flow was increased to ~430 MMSCFD, at which point operators observed excessive piping vibration at the raw-gas inlet and the test was stopped. Subsequent testing at 430 MMSCFD on all trains confirmed that vibration issues were localized to specific locations on Trains 1 and 2, while Trains 3 and 4 remained within EI limits.

4.2. Measurement Positions and Evaluation Criteria

The assessment focused on the 18″ raw-gas lines upstream of coalescer filters and associated bypasses and small-bore branches. Measurement positions were numbered (e.g. Points 3, 4, 5, 6, 11, 14, 15, 16, 20, 21, 25) and located at:

- Dead-leg branches around emergency shutdown valve 330-ESDV-003 (Points 3 and 4).
- Braced bypasses near MOVs and the MEG injection line (Points 5, 6, 14, 15, 20, 21).
- Curved sections and tees in the injection and bypass lines (e.g. Point 11).

The EI guideline "traffic light" approach was used:

- **Acceptable:** measured RMS velocity below the lower EI limit for process piping at the relevant frequency.
- **Concern line / concern area:** RMS velocity between the lower and upper EI limit or with occasional peaks above the limit.
- **Problem:** sustained RMS velocity exceeding the upper limit.

Velocity spectra and overall RMS values were acquired in three directions at each point, and the resultant RMS was compared with EI curves as a function of dominant frequency.

4.3. Week-41 Results on Trains 1–4

Table 1 summarizes the status of key points during Week-41 tests at 430 MMSCFD before any mitigation actions.

Table 1 – Summary of Week-41 vibration assessment at 430 MMSCFD (before mitigation).
(Adapted from the plant technical assessment.)

VIBRATION TECHNICAL ASSESSMENT …

Train	Status of measured points
Train 1	Point 5: concern area; Points 14 and 15: concern line. Other points within acceptable limit.
Train 2	Points 3, 4, 6, 11, 14, 16: concern area; Point 15: concern line.
Train 3	All measured points within acceptable limit.
Train 4	All measured points within acceptable limit.

The most severe responses were concentrated around **Train-2 ESDV-003 PT branches (Points 3 & 4)** and around bypass bracing near **Points 14–16**. Spectral analysis showed dominant frequencies near 35–36 Hz at dead-legs and around 51–52 Hz at some bypass spans, with resultant RMS velocities up to roughly 9–13 mm/s prior to mitigation—above the EI "concern" threshold for small-diameter branches in gas service.

train 2 at 430 mmscfd at 17-10-…

4.4. Mitigation Actions and Week-42 Re-assessment

A detailed investigation showed that Train 2 was unique in the way its reinforcement bracing was installed around the ESDV-003 pressure-tap dead-legs (Points 3 & 4). Two orthogonal bracing planes of similar stiffness allowed simultaneous excitation of both horizontal and vertical modes, increasing the resultant vibration amplitude compared with other trains where only one bracing plane was present or bracing tied the branch closer to the main-line flange.

VIBRATION TECHNICAL ASSESSMENT …

The main mitigation measures implemented were:

- **Re-design of ESDV-003 PT support (Train 2, Points 3 & 4):** a special support with additional mass on the dead-leg was installed. This increased local stiffness and shifted the natural frequency away from the excitation frequency. Resultant RMS vibration at 430 MMSCFD decreased by approximately 70%, falling well below EI concern limits.
- **Bypass bracing bolt management (Points 5, 6, 14, 15 and similar):** during Week-41 measurements, many clamps on braced bypass lines were found with loose bolts. After proper tightening, RMS velocities at all these points fell into the acceptable region. The assessment recommended installing longer bolts where necessary, using anti-vibration

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

washers (e.g. Nord-Lock or serrated DIN 6798) and double-nut arrangements to prevent self-loosening.

VIBRATION TECHNICAL ASSESSMENT …

- **MEG injection line support:** all trains exhibited low-frequency vibration on the MEG injection line. A pipe-to-pipe support was designed to connect the MEG line to a stiffer neighboring line and reduce response amplitudes (Section 8 of the assessment).
- **Weld NDT:** because some locations had experienced elevated vibration for a limited period, the report recommended targeted non-destructive examination (NDT) of high-stress welds to confirm that no fatigue cracks had initiated.

VIBRATION TECHNICAL ASSESSMENT …

Table 2 gives a condensed view of post-mitigation results.

Table 2 – Week-42 status at 430 MMSCFD after mitigation.

VIBRATION TECHNICAL ASSESSMENT …

Location / points	**Train 1**	**Train 2**
ESDV-003 PT branches (Points 3 & 4)	No issue	Special support + added mass; vibration well within EI limit.
Bypass near coalescer (Points 5 & 6)	Originally concern area due to loose clamps; acceptable after re-tightening	Same pattern; acceptable after re-tightening.
Bypass / branch near MEG injection (Points 14 & 15)	Concern line with loose bracing; acceptable after re-tightening	Acceptable at 430 MMSCFD; occasional peaks but average RMS within EI limits. Optimization recommended.
Downstream bends (Points 20 & 21)	No issue	Within limit but close to threshold; further optimization recommended.
Curved injection line (Point 11)	No issue	Acceptable.

Overall, after mitigation, all monitored locations on Trains 1 and 2 were within EI limits at 430 MMSCFD. Nonetheless, the assessment recommended further optimization and more detailed

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

dynamic analysis—especially at locations near EI "concern" thresholds—to improve long-term margins and reduce the risk of fatigue cracking.

4.5. Train-6 Vibration Survey on the 18″ Inlet Line

In April 2019, a dedicated vibration survey was performed on the 18″ raw-gas inlet line of **Train 6** to confirm behavior at high throughputs and to evaluate the influence of inlet-valve position.

TR6

The train was tested at three operating conditions:

- 350 MMSCFD, 81.5 bar upstream / 77.16 bar downstream, valve opening 68%.
- 400 MMSCFD, 81 bar / 76.85 bar, valve opening 66.7%.
- 420 MMSCFD, 81 bar / 76.8 bar, valve opening 68.7%.

  TR6

Measurements were taken at Points 3, 4, 6, 11, 14, 15, 16 and 25 on the inlet line and associated branches, using the same tri-axial RMS velocity approach and EI criteria as for the earlier campaign. The results can be summarized as follows:

- **At 350 MMSCFD:** all points were classified as **accept**.
- **At 400 MMSCFD:** Points 3, 4, 6, 11, 16 and 25 remained acceptable; Point 14 was classified as **concern line**; Point 15 remained acceptable.
- **At 420 MMSCFD:** Points 3, 4, 6, 11 and 16 remained acceptable; Point 25 was classified as **concern line**; Points 14 and 15 showed **concern line** and **accept**, respectively.

No locations were classified as "problem" according to EI criteria. However, the emergence of "concern line" classifications at high flow on Points 14 and 25—corresponding to braced bypass spans and small-bore connections—suggests that these details are dynamically sensitive and warrant ongoing monitoring and optimization, particularly if future operation at or above 430 MMSCFD is planned.

4.6. Discussion of Case-Study Findings

Several patterns from the Zohr case study align closely with trends reported in the literature:

1. **Concentration of risk at geometric discontinuities and small-bore branches.** Most concern locations (e.g. ESDV-003 PT branches; Points 14 and 25) are short dead-legs or SBCs attached to the main 18″ line, consistent with reported field failures in other facilities (Matta & Szasz, 2018; Cheong, 2024).

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

2. **Sensitivity to support conditions and bolt integrity.** Loose bypass-bracing clamps were the dominant reason why some points exceeded EI limits. After proper tightening and simple hardware upgrades (longer bolts, anti-vibration washers, double nuts), vibration fell into the acceptable region without major layout changes—illustrating how small changes in stiffness and boundary conditions can significantly alter dynamic response.

   VIBRATION TECHNICAL ASSESSMENT …

3. **Effectiveness of targeted damping and stiffening.** The special support and added mass on Train-2 ESDV-003 PT reduced resultant RMS velocity by about 70%, similar to the reductions reported for tuned mass dampers and PTMDs in the literature (Tan et al., 2019; Lin et al., 2025).
4. **Importance of conservative screening and follow-up analysis.** Initial EI-based screening successfully highlighted the problematic locations, but further spectral analysis and structural review were required to design effective mitigation, particularly for borderline "concern line" cases. This mirrors the broader conclusion that screening tools are excellent for triage but must be supplemented with detailed analysis for critical systems.

Taken together, the Zohr case study demonstrates that vibration-induced fatigue risk can be managed effectively by combining systematic screening, disciplined field measurement, and relatively simple but targeted mitigation actions. At the same time, it underlines the need for continuous monitoring of sensitive locations and for design optimization when capacity increases push operation closer to dynamic limits.

5. Synthesis of Literature and Case Study

The literature review and field experience points towards a set of consistent themes:

- **Dominant failure drivers.** FIV and AIV remain the two main mechanisms behind vibration-induced fatigue failures in gas-processing piping, particularly at weld toes and SBCs located near pressure-reducing devices or in long, flexible spans.
- **Limitations of first-pass screening.** EI and ASME screening charts are indispensable tools, but they are derived under simplifications (steady-state, single-phase, ideal supports). As shown by both literature and the Zohr experience, borderline cases and complex multiphase regimes often require additional modal analysis, time-history simulations or on-site measurements to quantify actual risk.
- **Value of high-fidelity modelling.** Acoustic–structural FEA and FSI models can accurately predict dynamic stress ranges and fatigue lives when supplied with realistic boundary conditions and load data. Their greatest value lies in high-consequence

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

locations (e.g. large pressure drops, thin-wall branches, critical containment boundaries) where failure consequences justify the modelling effort.

- **Effectiveness of hybrid mitigation strategies.** Structural changes (additional supports, clamps, layout modifications), dynamic devices (TMDs, PTMDs, vibro-impact dampers) and material enhancements often need to be combined. In retrofit situations—such as the Zohr inlet lines—relatively simple measures like stiffening, added mass and improved bolting were sufficient. In other cases, advanced dampers or material treatments may be more appropriate.
- **Role of field data and monitoring.** Case studies repeatedly show failures occurring when actual operating conditions deviate from the design envelope or when retrofits unintentionally introduce new vibration paths. Systematic monitoring programs, using permanent or periodic measurements, are essential to detect evolving vibration issues and to validate model predictions over the asset life cycle.

For gas-processing plants considering capacity increases, these insights suggest the need for a proactive vibration-management plan integrated into both project and operational phases.

6. Conclusions and Recommendations

This paper combined a structured review of recent research on vibration-induced fatigue in gas-processing piping with a detailed case study from the Zohr onshore gas plant.

Key conclusions are:

1. **Vibration-induced fatigue is a systemic integrity risk.** FIV and AIV can generate alternating stresses sufficient to initiate and propagate cracks at common piping details, especially SBCs, dead-legs, reducers and poorly supported spans. The risk is heightened when throughput increases or layouts become more compact.

   High-Cycle Fatigue Failure Analysis

2. **Guideline-based screening is necessary but not sufficient.** EI and ASME methods are effective first steps but may under- or over-estimate risk in complex multiphase or transient conditions. Borderline cases should trigger more detailed analysis and/or field measurement.
3. **Targeted mitigation can dramatically reduce vibration.** At Zohr, redesigning a dead-leg support with added mass and tightening bypass bracing bolts decreased RMS velocities by up to ~70% and brought all monitored locations within EI limits at 430 MMSCFD. Similar reductions are reported in the literature for tuned mass dampers and vibro-impact systems.

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

4. **Small details matter.** Bolt length, washer type, clamp condition and actual stiffness of local supports had a decisive influence on vibration levels in the case study. Such details must be considered explicitly in both modelling and site inspections.
5. **Continuous monitoring and life-cycle thinking are essential.** Because dynamic loads can change over time as operating conditions evolve, one-off assessments are not enough. Periodic re-measurement, inspection of high-risk welds and updating of models and mitigation measures are required to maintain mechanical integrity throughout the facility life cycle.

Based on these findings, the following actions are recommended for similar facilities:

- Integrate vibration screening into all capacity-increase assessments and major modifications.
- Systematically identify and catalogue small-bore connections and dead-legs, including their support conditions, and treat them as priority inspection locations.
- Use high-fidelity numerical modelling selectively for high-consequence or borderline locations.
- Where practicable, deploy dynamic mitigation devices or advanced materials in addition to conventional supports, especially in retrofit situations.
- Establish a vibration-monitoring and inspection plan that is aligned with risk, including EI-based acceptance criteria and scheduled NDT of critical welds.

Acknowledgements

The author thanks the Zohr onshore plant operations and maintenance teams, as well as the engineering staff who contributed to the vibration measurement campaigns and mitigation design. [Add any additional acknowledgements required by your organization or journal.]

References

(Format this list according to the journal's reference style; below is an example in a generic author–year format, based on the sources in your draft manuscript.)

1. Ahmed, F., et al. (2017). [Title on vibration failures in pump-driven systems].
2. Ahmed, F., et al. (2022). *Acoustics and vibrations in a complex piping network with reciprocating pump dynamics.* Journal of Fluids and Structures. https://doi.org/10.1016/j.jfluidstructs.2022.103456.
3. Al Sawwafi, M. (2022). [Study on recurrent vibration issues in retrofitted piping].

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 06-12-2025

4. Aloschi, F., Andreotti, R., & Bursi, O. S. (2023). Pipe vibration attenuation through internal damping and optimal design of vibro-impact systems. *Scientific Reports, 13*, 6510. https://doi.org/10.1038/s41598-023-33640-y.

5. Antaki, G. (2023). Flow-induced vibration of piping systems. *ASME PVP* Proceedings. https://doi.org/10.1115/PVP2023-1171379.

6. Cheong, I. T. (2024). The use of tuned mass dampers in mitigating small-bore piping vibration. *ASME PVP* Proceedings. https://doi.org/10.1115/PVP2024-124807.

7. Coulon, A., Salanon, R., & Ancian, L. (2018). Innovative numerical fatigue methodology for piping systems: qualifying acoustic-induced vibration in the oil & gas industry. *Procedia Engineering, 213*, 762–775. https://doi.org/10.1016/j.proeng.2018.02.072.

8. Ding, H., & Ji, J. C. (2023). Vibration control of fluid-conveying pipes: a state-of-the-art review. *Applied Mathematics and Mechanics (English Edition), 44*(9), 1423–1456.

9. Emmerson, P. R. (2020). Flow-induced vibration analysis of topside piping at high pressure. *OMAE 2020* Proceedings. https://doi.org/10.1115/OMAE2020-1092923.

10. Haile, A. (2022). [Work on FIV mechanisms in gas-processing pipelines].

11. Lin, S., et al. (2025). Experimental and simulation study of pounding tuned mass dampers for gas–liquid jumper systems. *Physics of Fluids*. https://doi.org/10.1016/j.physfluids.2024.117107.

12. Matta, L. M., & Szasz, G. (2018). Vibration and fatigue failures at pipeline facilities. *Proceedings of the 12th International Pipeline Conference*. https://doi.org/10.1115/IPC2018-78176.

13. Moussa, M. (2013). [Case study on AIV-induced failures during blowdown].

14. Naderpour, H., et al. (2024). [Study on pipeline mass dampers under seismic and operational loads].

15. Pontaza, J. P. (2021). A frequency-domain screening methodology for flow-induced vibration in piping. *OMAE 2021* Proceedings. https://doi.org/10.1115/OMAE2021-64060.

16. Ridens, B. L., Allison, T. C., Simons, S., & Brun, K. (2018). Modeling and mitigation of acoustic-induced vibration (AIV) in piping systems. *PSIG Annual Meeting* Proceedings.

17. Saeed, A., et al. (2021). [Boronizing treatment for improved fatigue resistance under acoustic loading].

18. Tan, J., Ho, S. C. M., Zhang, P., & Jiang, J. (2019). Experimental study on vibration control of suspended piping system by single-sided pounding tuned mass damper. *Applied Sciences, 9*(2), 285.