UKOPA
United Kingdom Onshore Pipeline Operators' Association

UKOPA Good Practice Guide

Management of Pipework Vibration

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1. EXECUTIVE SUMMARY

This guidance aims to give background knowledge on the cause and effect of vibration, how to identify, measure, monitor and if necessary, implement any mitigation or remedial actions to prevent failure through vibration on above ground piping and associated equipment.

2. INTRODUCTION

2.1 Background

There have historically been a number of vibration-related fatigue failures of pipework at Above Ground Installations (AGIs). The following list outlines some of the incidents experienced:

- **Failures at threaded connections**

  Threaded connections are a potential site for initiating a fatigue crack, due to the local stress concentration factor at the root of the thread, with the stress distribution being highest at the first engaged thread as it enters the valve body or flange. Fatigue cracks can initiate at this location if the fatigue loading is high enough.

- **Failures at welds**

  The toe of a fillet weld is a potential site for fatigue failures, due to the local stress concentration factor of the weld toe and the presence of slag intrusions (microscopic imperfections) which exist there, and from which fatigue cracks may propagate. Therefore, in both these instances, fatigue cracks can readily initiate, and the fatigue life is dominated by fatigue crack growth if stresses due to vibration are sufficiently high.

- **Failures at compression fittings**

  Fatigue failures have also occurred on impulse pipework at compression fittings, with the failure originating from where the ferrule of the compression fitting is located on the pipe.

2.2 Scope

This good practice guide provides guidance on identification and management of pipework vibration on AGIs. Guidance is based on the Energy Institute document Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework [1], relevant standards [2] [3] [4] and operator internal documents.

2.3 Application

The guidance in this document is applicable to high pressure AGIs.

Within this document:

Shall: indicates a mandatory requirement.

Should: indicates good practice and is the preferred option.

3. CAUSES OF VIBRATION

The main causes of vibration related problems are:

3.1 Flow Induced Turbulence

Flow induced turbulence can be severe if the flow velocities are high, the flow path is tortuous or major flow discontinuities occur in the system (typical examples are partially closed valves, short radius or mitred bends, tees or reducers).

3.2 Mechanical Excitation

Mechanical excitation can occur in systems containing reciprocating/positive displacement compressors and pumps. The dynamic forces produced in the equipment will result in excitation of connected pipework or common support structures. This cause issues with pipework which shares supports with the equipment or associated pipework but is not part of the system causing the excitation. This can transfer of dynamic forces can result in excitation of pipework close to a machine. Vibration issues are generally located in proximity to the equipment generating the mechanical excitement.

3.3 Pulsation

Excitation of acoustic natural frequencies, which can amplify low levels of pressure pulsation in a system to cause high amplitude pressure pulsations, leading to excessive shaking forces. For the most serious vibration problems, the frequency of excitation, acoustic natural frequency and structural natural frequency may coincide (i.e. a resonant condition). High frequency acoustic energy can be of particular concern as it tends to affect safety related (e.g. relief and blowdown) systems, in addition to which the time to failure is short (typically a few minutes or hours) due to the high frequency response.

Gas systems, at relatively high flow velocities, can exhibit a form of tonal excitation which is generated when flow past the end of a dead leg branch generates an instability at the mouth of the branch connection.

Some thermowells or other probes which extend into the flow stream (e.g. chemical injection quills or flow measurement probes) may also be susceptible to resonant excitation caused by vortex shedding.

3.4 High Frequency Acoustic Excitation

Severe sources of vibration energy associated with the process conditions or the geometry of the flow path. At a gas AGI the dominant source is likely to be the pressure drop occurring at each regulator.

3.5 Surge

Surge (or water hammer) is a pressure wave caused by kinetic energy of a fluid in motion when it is forced to stop or change direction abruptly. High transient forces can be generated by the rapid change in fluid momentum caused by situations such as the sudden opening of a valve, e.g. fast opening of a relief valve, or changing flow direction to one with no through route e.g. dead-heading the flow.

3.6 Cavitation

Cavitation can occur where a localised pressure drop occurs in liquid systems and is followed by a pressure recovery, e.g. at a control valve or restriction such as an orifice plate. If the pressure falls below the vapour pressure of the liquid, vapour bubbles will form. When the pressure recovers to greater than the vapour pressure, these bubbles collapse, releasing energy, causing noise, damage to mechanical components and vibration.

3.7 Flashing

If the pressure in a pipe become less that the vapour pressure of the fluid, the fluid can suddenly change from liquid to vapour, resulting in This results in large forces. This typically occurs when there is localised pressure drop in the process fluid or when two fluid types mix.

3.8 Vulnerable Geometry

Small bore attachments can experience vibration problems when there is a cantilevered pipe with a large mass on the end (for example flanges or valves) a long unsupported of piping run or poorly/incorrectly constrained section. Vulnerable pipework connections such as fillet welds and sockolet fittings are also susceptible.

4. VIBRATION CONSEQUENCES

Vibration can result in loss of containment through two processes:

4.1 Fatigue

Vibration results in dynamic stresses. If these are above a critical level, they can initiate and/or propagate a fatigue crack. Cracking can result in through thickness failure and loss of containment if not remediated. An example of a fatigue crack induced in regulator pipework is shown in Figure 1.

Figure 1 Vibration induced Fatigue Crack on Regulator Pipework

Welded joints associated with main lines and small-bore connections are the most sensitive to fatigue. Failure typically occurs at the connection of the small-bore connection and the main line pipe but can occur at other weld locations.

4.2 Fretting

Fretting occurs when two surfaces are in contact and subject to cyclic relative motion. This can result in loss of wall thickness of one of both surfaces and ultimately loss of containment. An example of vibration induced fretting on impulse pipework is shown in Figure 2.

Figure 2 Vibration induced fretting on Impulse Pipework

5. DESIGN GOOD PRACTICE

This guidance focuses on in-service installations. The following are notes to consider at the design stage.

The preferred method of mitigating vibration related issues is to consider vibration during the design and commissioning stage. There is design guidance in IGEM/D/13 (Appendix 5) [4] and Energy Institute document 'Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework' [1].

5.1 Temperature Monitoring

Vibration of any thermowells due to vortex shedding can be a threat to both the thermowell and the instrument stabbing and should be assessed using the methods in ASME PTC 19.3 [5]. If the thermowell is required for operational reasons but is considered to be at risk of vortex shedding, it should be replaced with a surface mounted temperature probe, unless temperature response time is critical. For those cases which still require a thermowell, one-piece forged, flanged thermowells should be used, together with weldoflange type instrument stabbings.

5.2 Noise

Where noise does not pose a threat to the pipework integrity, if it cannot be reduced to acceptable levels then there is the option of installing acoustic cladding, or lagging the pipework and valves to reduce the emission of noise, however, the risks relating to initiation of corrosion of the pipework must be carefully managed.

6. VIBRATION IDENTIFICATION

Where indicators of high vibration and/or pipework problems potentially caused by vibration are observed, then further investigation should be undertaken as described below.

6.1 Overview

Visual inspection should be undertaken at various operating conditions. It is recommended that operational staff are interviewed regarding their experience of when vibration has occurred and under what conditions. The process and operating conditions under which the vibration and/or noise occurs should be noted, for example operating pressures and temperatures, the operating regime of nearby equipment, and flow rates.

Absence of high noise and/or vibration levels during visual inspection should not be taken as necessarily being indicative of there being a low risk from vibration induced fatigue.

If fatigue cracking is identified in the vicinity of small-bore connection welds on a main pipe, either during a routine inspection or as reported by site technical staff, or pipe wall thickness loss due to fretting wear, then appropriate action should be taken urgently.

The following should be used as guidance for visual inspections in order to identify whether pipework might be at risk of experiencing excessively high levels of vibration:

6.1.1 Indicators of high vibration being present on the pipework:

- Main pipework, branch connections, or impulse pipework felt to exhibit excessive vibration when touched by hand (e.g. feels uncomfortable to touch)
- Rattling of any attached or nearby instrument panels or enclosures
- Evidence of fretting wear (loss of wall thickness) on pipework in contact with another component (e.g. thermal/acoustic cladding, other pipework, supports, branch connection)
- BPCS vibration or condition monitoring systems and associated alarms or trips

6.1.2 Areas where pipework issues may be due to high vibration levels:

- Main pipework support incorrectly aligned (e.g. gap between pipe and support) or missing supports
- Long un-supported sections or small-bore pipework
- Small bore pipework systems with significant cantilevered mass e.g. valve
- Excessive corrosion of threaded section of fittings
- Insufficient clearance between pipework and another component (e.g. thermal/acoustic cladding, other pipework, supports, branch connection)
- Damaged or broken supports

6.2 High Vibration/Noise

There are three attributes to look for:

1) Pipework that can be seen to be vibrating is indicative of low frequency vibration

2) Pipework that can be felt to be vibrating is indicative of low to medium frequency vibration

3) Pipework exhibiting high noise is indicative of high frequency vibration

Ideally vibration and/or noise levels should be quantified using an appropriate measurement survey.

6.3 Fretting Damage

Typical locations to be investigated include:

- U-bolt pipe clamps
- Resting supports
- Loose insulation cladding
- Pipe contact
- Pipework in contact with other equipment (e.g. cable trays, handrails, fittings)
- Temporary supports

If fretting is identified, the items should be separated, and the damage quantified and assessed.

6.4 Small Bore Connections

There are various considerations to determine the susceptibility of a connection to fatigue damage [5]. There include:

- Type of fitting. The following list of fittings ranks their resistance to vibration, from good at the top, to poor at the bottom:
    - Short contoured body
    - Contoured body / welded tee / forged reducing tee
    - Weldolet / threadolet fully back welded / screwed fully back welded
    - Threadolet / screwed
    - Threadolet partially back welded / screwed partially back welded
    - Set-on / set-in / set-through

- Length of fitting. The greater the distance from the connection to the parent pipe to any unsupported mass, the more susceptible the fitting to fatigue.
- Mass loading. The greater the mass on a connection, the more susceptible the fitting to fatigue.
- Diameter of fitting. The smaller the diameter, the more susceptible the fitting to fatigue.
- Parent pipe wall thickness. The thinner the wall, the more susceptible the fitting to fatigue.
- Location of connection on parent pipe. The closer a small-bore connection is to an anchor location on the parent pipe, the less susceptible the fitting to fatigue. Conversely if a connection is located at a mid-span or close a discrete energy source (e.g. valve, orifice plate), the more susceptible the fitting to fatigue.

6.5 Pipe Supports

Features to consider regarding supports are:

- Damaged or missing supports.
- Temporary supports (e.g. rope, wooden supports)
- Supports that are not adequately stiff relative to supported pipe
- Incorrectly placed supports e.g. at a point of zero vibration amplitude

6.6 Bracing of Small-Bore Connections

The following are considerations which can result in fatigue issues even when a connection has been braced:

- Unsuitable bracing (e.g. wood blocks, rope, cable ties)
- Brace not supporting free mass on the connection end
- Brace only supporting the first weld
- Bracing in only one plane
- Connection not braced back to parent pipe (e.g. neighbouring structure or adjacent pipe)
- Use of welded gusset plates on pipework without reinforcing plates (notably for thin walled pipes)
- Loose bolts on bolted clamps

6.7 Instrument Tubing

Failure due to vibration of instrument tubing predominately occurs at connections. As instrument tubing does not have welded connections it allows a greater degree of dynamic stress before fatigue cracking initiates. Instrument tubing should allow differential movement of the two connecting items. There should be no direct tubing connecting two points.

7. VIBRATION MEASUREMENT TECHNIQUES

Vibration measurement techniques measure vibration acceleration, velocity and displacement. or dynamic strain as a function of time, which is then analysed to generate the vibration stress – frequency spectra. Specialist advice is required to achieve accurate vibration measurement and analysis in order to identify and calculate fatigue life [2] [3].

7.1 Vibration Velocity Measurement

Vibration velocity is the maximum speed reached during the vibration cycle. Vibration velocity measurements provide a simple method for screening a piping system for vibration problems. Measurements are obtained at a number of locations using accelerometers and data loggers. The advantage of this technique is the relative ease of measurement obtainment. The disadvantage is that the data cannot be used to derive an estimate of fatigue life.

7.2 Direct Dynamic Strain Measurement

Direct dynamic strain is measured using either permanent or portable strain gauges. The measurements provide a comprehensive assessment of the likelihood of fatigue failure, as it enables dynamic stress to be calculated. The main disadvantages are that specialist equipment is required and the location of the strain gauges is critical to deriving a representative stress.

7.3 Vibration Fast Fourier Transform (FFT) Measurement

The fast fourier transform (FFT) is used to transform vibration displacement or amplitude measurements as a function of frequency. This technique measures appropriate velocity, amplitude and acceleration data for use in Finite Element Analysis (FEA) models for the prediction of fatigue life and the design of suitable supports.

7.4 Motion Amplification

In addition to measurement of vibration amplitude and frequency, video processing and software can be used to detect and amplify motion, which is not visible to the human eye, This is a specialist proprietary technique, which magnifies movement and allows non-invasive visualisation of vibration [6].

8. REMEDIAL AND MITIGATION MEASURES

Where there is a pipework vibration problem, the severity of the problem will determine the timescale for implementation of the mitigating actions required.

To reduce the risk to an acceptable level, different options may be considered dependent on the vibration source. These can be grouped into those that modify the excitation mechanism and those modifying the response mechanism. If practicable, the excitation mechanism should be addressed to reduce or remove the excitation energy and vibration response.

In cases of multiple excitation mechanisms, the remedial action should address all excitation mechanisms.

Remedial options could include the following:

- Tightening up clearance on supports. This produces a similar effect to adding supports, stiffening the pipework and altering the natural frequency. If an existing support permits pipework to move it can be the cause of excessive vibration. By tightening the clearance on supports the pipework natural frequency is increased, normally resulting in reduced vibration (typically the levels of energy fall with increased frequency). This is not always possible as thermal expansion may be accounted for in the support.

- Avoid metal-to-metal contact. The two surfaces should be separated to remove the risk of fretting. If contact is necessary (for example a pipe support) then a wear resistant or compliant surface should be used between the surfaces

- Stiffening the system via additional supports. This will increase the natural frequency resulting in reduced levels of vibration. Consider adequate support at sources of turbulence (for example valves, mitred bends) to reduce coupling between turbulent energy generated by the source and the piping. Care needs to be exercised in the placing of supports to ensure they work as intended. Placement should be based on direct measurement data and/or vibration modelling.

- Checking the alignment of pipework sections to identify whether misalignment is causing stress and vibration issues.

- Conduct a surge analysis to determine the magnitude of any surge and identify appropriate mitigation measures.

- Quantify surge hazards and the effect of mitigating measures such as the use of surge alleviators, anti-surge valves (PCV's), changing system timings (in controlled shutdowns only) and or other process controls to avoid dead-heading scenarios.

- Changing span length or support types to avoid resonant conditions.

- Changing the diameter, wall thickness, or pipework layout to change the response.

- Changes in components (valves, bend/tee radius) to reduce turbulence.

- A change in operation (velocity, pressure, flow path) to avoid resonance, or flow induced pulsations.

- Removal, redesign or bracing (permanent or temporary) of small-bore connections.

- Modified operation. If the vibration source is due to flow induced turbulence, reducing the fluid velocity will reduce the excitation energy and therefore the response of the pipework. Fluid velocity decreases can be achieved by increasing the diameter of the main pipe, running a second parallel pipe or changing the operating conditions. Consider flow smoothing and/or changing the valve type.

- More regular checking or non-destructive testing. This increases the likelihood of identifying and vibration and related fatigue cracking.

- Viscous dampeners. Stiffening of the system is not always appropriate. Vibration dampers can be an effective vibration mitigation as they allow relatively large movement whilst providing damping. Note these are ineffective at frequencies over 30Hz or for narrow band excitation.

- Shock arrestor / absorber / snubber. Thermal growth requirements may limit additional support. Shock arrestors allow low velocity movement but provide resistance for sudden movements caused by forced vibration. Shock arrestors lock in position at certain level so can result in high applied loads during slugging.

- Composite wraps. Composite wraps can beneficially stiffen a main line, but the increased weight could negate the benefit. Composite wraps also increase damping levels which may reduce the vibration response. Currently there is a lack of knowledge on the effects of high-cycle fatigue resistance of composite wraps.

- Increased wall thickness. This will result in a lower dynamic stress level for a given level of excitation. For a given diameter, an increased wall thickness will increase the fluid velocity and with it the turbulent excitation. The realised benefits outweigh this negative effect.

Any modifications should be assessed to understand the implications of the proposed changes. Design documentation should be updated to reflect any changes made, and drawings and document updated as appropriate.

Where sections have been identified as being at high risk, a check should also be undertaken for similar pipework locations on the same or other sites that may therefore also be at risk. Mitigation across all similar sections should avoid the problem being repeated elsewhere.

9. SPECIALIST PREDICTIVE TECHNIQUES

The following table identifies applicable predicative techniques for various excitation and response mechanisms:

Excitation mechanism	Structure finite element analysis	Acoustic finite element analysis	Computational fluid dynamics (CFD)	Pulsation analysis	Surge analysis	Valve sizing calculations
Flow induced turbulence	✓		✓			
Mechanical excitation	✓					
Pulsation: Reciprocating/positive displacement pumps and compressors	✓	✓		✓		
Pulsation: Rotating stall	✓	✓		✓		
Pulsation: Flow induced excitation	✓	✓		✓		
High frequency acoustic excitation	✓					
Surge/momentum changes dues to valve operation	✓				✓	✓
Cavitation and flashing	✓		✓			✓

Table 1 Applicable predictive techniques for the various excitation and response mechanisms

10. REFERENCES

[1] Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework, Second Edition,, Energy Institute, 2008.

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[3] BS 7608:2014 ‘Guide to fatigue design and assessment of steel products’, BSI, 2014.

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