Technical primer:
Piping vibration studies

For more information, contact Wood's vibration, dynamics & noise (VDN) team at info.vdn@woodplc.com or visit vdn.woodplc.com for local support.

Introduction

This primer discusses studies available to ensure piping vibration does not lead to fatigue failure. The studies depend on the information available.

Piping vibration is typically evaluated on continuously operating main process lines of any size and small-bore branch connections that are nominal pipe size (NPS) 2″ and below. Intermittently operated lines and lines subject to transient forces may require specialized analysis.

The information required for an analysis includes:

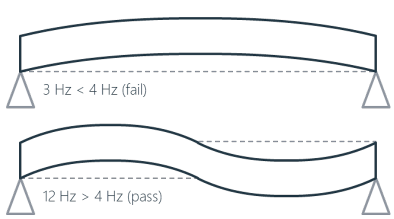
- Piping isometrics or general arrangement drawings
- Support details, including structural members
- Equipment and valve datasheets
- Fluid properties including flow rate, void fraction, density, molecular weight, pressure, temperature, bulk modulus, and viscosity (optional)
- Field vibration measurements (optional)

Finite element model

For most evaluations, a finite element (FE) model is created in software programs like ANSYS™. Programs like Caesar II™ can only be used for modal and dynamic analyses, but not allowable vibration analysis (because stresses from a modal analysis are not reported).

If only bending modes are of concern, then one-dimensional (1D) elements (eg, beam or pipe) are acceptable if intersections, like small bore connections (SBCs), are modelled with the correct stiffness and stress intensification factor (SIF). For high-frequency shell modes or complex geometries, 2D or 3D elements (ie, shell or brick) may be required.

Modal analysis



The easiest approach is to run a modal analysis, where the piping natural frequency (NF) is calculated for different vibration mode shapes. In the example shown, the first and second modes of a simply supported (pinned-pinned) beam are calculated and compared to the DNV guideline.

Natural frequency guidelines

The piping NF can be compared to different guidelines, like DNV [5], EI [1], API [6], and GMRC [4].

For main line piping subject to flow-induced turbulence (FIT), ensure the piping NF > 4 Hz [5]. Depending on the excitation mechanism, the recommended minimum NF can vary from 4 Hz – 15 Hz [1].

For main line piping subject to pulsations and unbalance from reciprocating compressors, the recommended minimum NF is 2.4x compressor running speed [6].

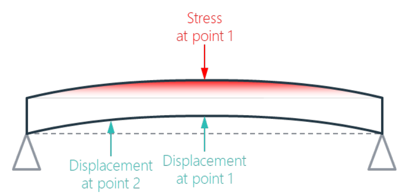
For SBCs subject to FIT forces, ensure the SBC NF > 25 Hz (single-phase fluid) or >50 Hz (multi-phase fluid) [7].

For SBCs subject to pulsations and unbalance from reciprocating and rotating machinery, the recommended minimum NF depends on the machinery, running speed, and proximity to the machinery, but is generally 20% above the dominant pulsation frequency [4]. For example, SBCs near reciprocating compressors should have NF > 4.8x compressor running speed.

Allowable vibration analysis

To ensure field-measured vibrations do not result in dynamic stresses that exceed the piping material and weld fatigue limit, an allowable vibration analysis can be done, which builds on the modal analysis. (While field-measured displacements can be directly applied to an FE model, the resulting static stress may not accurately represent the actual dynamic stress.)

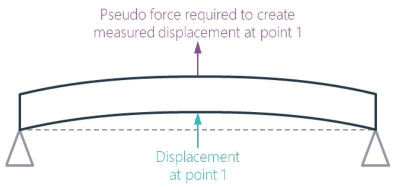
This study provides the maximum vibration in a specific direction, at a particular measurement point, for a particular mode shape, that ensures the stress anywhere in the piping system remains below the fatigue limit. This involves calculating the stress per displacement (*s/d*) or stress per velocity (*s/v*) factors.



In the example shown, the vertical vibration at point 1 must be kept below the allowable velocity, v_{all}, so the stress remains below the constant allowable fatigue limit (CAFL) from fatigue standards like BS 7608 [1]. If measurements are taken at point 2, there will be a different v_{all} calculated. Typical piping vibration on continuously operating systems builds fatigue damage so quickly that designs must be kept in the infinite life region in most cases.

Note that while pressure-containing piping fatigue failure is a primary concern for vibration, other concerns may include operator comfort and damage/fretting of other components like clamp bolts, insulation, tubing, and valve internals. This is outside the scope of an allowable vibration study.

Pseudo-dynamic forces



The allowable vibration analysis does not predict vibration amplitudes; it only ensures measured vibrations are acceptable for fatigue.

Calculating dynamic forces from fluid flow is difficult, whether it comes from pulsations created by reciprocating compressors, which require an API 618 study [6], pulsations created by reciprocating pumps, which require an API 674 study [8], multiphase fluid flow, slug flow, or waterhammer.

An intermediate step is to estimate the dynamic forces that would be required to match the vibrations measured during a field survey. The validity of this method depends on the quality and quantity of field vibration measurements and the nature of the excitation mechanism.

This study can be used to test how mechanical modifications, like braces or additional supports, can affect the vibration (and stress) amplitudes.

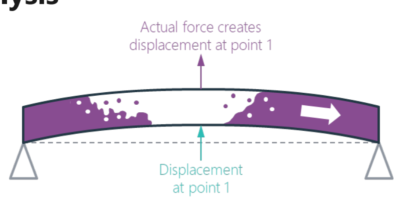
Video

In some cases, vibration measurements cannot be taken because the piping is inaccessible/elevated, too hot for vibration sensors, or severe vibrations occur occasionally or unpredictably. If video can be taken of the vibration instead, extracting the vibration amplitude, frequency, and mode shape from the stable footage may be possible.

Dynamic forces

To predict dynamic forces, the process conditions must be known. For example, slug forces depend on fluid velocity and density. Predicting dynamic forces may require specialized software like BOSpulse™, OLGA™, or even CFD. Some dynamic forces can be estimated from hand calculations or statistically correlated to experimental testing. Once the forces are known, a dynamic analysis can be done.

Dynamic piping analysis



Depending on the nature of the dynamic force, a dynamic piping analysis can be done:

- **Harmonic:** Periodic dynamic forces are applied at one frequency at a time (eg, thermowells subject to vortex shedding, piping subject to pulsations from reciprocating machinery)
- **Transient**: Temporary dynamic forces are applied over time (eg, check valve closing creating pressure pulse)
- **Random**: Unpredictable dynamic forces are applied statistically using a power spectral density (PSD) force (eg, flow-induced turbulent forces)

The resulting dynamic stresses are compared to fatigue limits.

Equivalent static load analysis

Two types of dynamic forces can be analysed statically:

- Slowly applied dynamic forces like wind or snow loads where the piping inertia is not dominant and can be ignored (called "quasi-static" loads).
- Transient impulse-type loads like slug forces and water hammer forces. These loads can be investigated using an equivalent static load (ESL) analysis, where the dynamic force is multiplied by a dynamic load factor (DLF) and then applied statically. Care must be taken to account for the interaction between subsequent forces, like two closely spaced slugs impacting an elbow.

Fatigue life

When forces are intermittent, like pressure safety valve (PSV) opening events, fatigue damage may accumulate slowly enough that a fatigue life calculation can be done using an S-N curve and Miner's Rule [2].

References

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

[2] British Standard BS 7608:2014+A1:2015, "Guide to Fatigue Design and Assessment of Steel Products", British Standards Institution, 2015.

[3] German standard VDI 3842, "Vibrations in piping systems", Association of German Engineers (Verein Deutscher Ingenieure), June 2004.

[4] Gas Machinery Research Council (GMRC), "Design Guideline for Small Diameter Branch Connections", Release 1.0, Mar 2011.

[5] Det Norske Veritas (DNV) Recommended Practice DNVGL-RP-D101 "Structural Analysis of Piping Systems", July 2017.

[6] American Petroleum Institute, API 618 "Reciprocating compressors for petroleum, chemical, and gas industry services", 2007.

[7] American Society of Mechanical Engineers, ASME PVP2024-122729, "Evaluating the Effectiveness of Bracing Designs in Reducing the Vulnerability of Small-bore Piping Connections to Vibration", 2024.

[8] API 674, "Positive Displacement Pumps — Reciprocating", 3rd Edition, Dec 2010.

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