# Specification for Pumping System Vibration Studies

**Mitigating Vibration on Centrifugal and Reciprocating Pumping Systems**
**Recommended Pump Design Requirements to Avoid Pulsation and Piping Vibration**

Centrifugal and reciprocating pumps, especially larger pump systems, generate vibration on the piping system. Unless properly mitigated, induced vibration will result in piping fatigue failure, reliability problems and excessive maintenance costs.

For example, one large pump operator reported that vibration of small bore piping is one of the major causes of integrity problems and piping failures (oil releases). An integrity and reliability plan needs to include vibration mitigation.

The following vibration specification outlines the recommended scope and options, and addresses the unique excitation sources between the two classes of pumps. Using this generic specification on new projects will ensure the design of the system will include the important elements needed to control vibration of the machinery and piping system.

## Define the Vibration Analysis Scope

The following chart highlights the excitation sources that contribute to vibration problems. It also summarizes vibration studies to be considered. The study scope is not a black and white issue, but is based on assessing risk factors and consequences:

- **Vibration risks**. Large and more complicated systems pose higher vibration risks compared to small simple units. Offshore production facilities (FPSOs and platforms) have substantially more risk due to structural resonance and restrictive space for piping layouts. Higher pressures, higher flow velocities, and a wide range of operating conditions also contribute to increased vibration risk.
- **Consequences**. Consider the impact of a pump or piping fatigue failure, including operator and public safety, downtime costs, repair costs, or other factors. If the consequences are high, a vibration study should be specified in order to help quantify and reduce the risks.

For any project, the vibration study should commence early in the process (during the preliminary design layout). Once the design is locked down, it becomes much more difficult and expensive to mitigate vibration risks and failures.

## Selection Table

The following table outlines vibration related studies that are performed during the design stage or if a plant is being modified. Contact BETA for application support.

Key:

- ✓ Analysis is generally required.
- ? Analysis is sometimes required based on the application (machine size, geometry, piping complexity, or user preference).

| Analysis Scope (recommendations and options for vibration analysis) | Pumping System (including driver and system piping) | |
|---|---|---|
| **Vibration Related Studies** | **Centrifugal Pump** | **Reciprocating Pump** |
| 1. **Front End Engineering & Design (FEED) Review** Evaluation of specifications, equipment layout, and vibration risks | ✓ | ✓ |
| 2. **Pulsation (Acoustical) and Mechanical Analysis** (API 674) for medium to critical applications, for pumps > 50kW | -- | ✓ |
| 3. **Piping Flexibility (Thermal) Stress Analysis** calculating Nozzle Loads and/or Environmental Loads (wave, wind, seismic) for large piping systems, hot liquids, or where inlet/outlet nozzle reaction load limits are severe. | ? | ? |
| 4. **Base Plate Design** for new configurations<br>**Dynamic Analysis** for dynamic loads<br>**Lifting Analysis** for safety/lifting code requirements | ? | ? |
| 5. **Foundation Design** for land based systems (evaluates soil conditions and applies to dynamic model<br>**Structural Dynamic Analysis** for onshore and offshore structural modules to address dynamic loads (this is beyond quasi-static analysis of wind or wave motion) | ? | ? |
| 6. **Torsional Vibration Analysis** for new (unverified) pump drivers combinations, loads, operating condition(s), and upset conditions | ? | ? |
| 7. **Small Bore Piping Design Review** for all small diameter branch connections on machine related piping or associated system. Scope should include field review. Also included in Piping Vibration Integrity Study, see #9, below | ✓ | ✓ |
| 8. **Water Hammer Transient Analysis** to avoid integrity risks of piping overpressure, vacuum (pipe collapse), and fatigue due to transient pressure surges in the piping system | ✓ | ✓ |
| 9. **Piping Vibration Integrity Study** (Plant Wide Assessment) to identify Risk of Vibration Induced Fatigue Failure per Energy Institute 2008. This review highlights critical locations in piping systems that have a high likelihood of failure (LOF). Includes machines and plant piping system. Screens all locations to identify high risk areas. For large plants/facilities with many different machines and complicated piping systems. Evaluates Acoustic Induced Vibration (AIV), Flow Induced Vibration (FIV), Pulsations, Surge, Water Hammer, etc. | | |

## Study Component – Specifications

Approved supplier: Beta Machinery Analysis

### 1. Front End Engineering & Design (FEED) Review

Vibration consultant to review project scope, proposed piping and machinery layout, pump specifications, foundation concepts, and proposed vibration mitigation plan. Provide comments and recommendations including:

- Vibration risks on pump packages and associated piping system
- Recommended vibration design and field guidelines
- Scope and specification details for vibration analysis
- Suggested process, responsibilities, timing and budgets

Summarize comments in letter report.

### 2. Pulsation (Acoustical) and Mechanical Analysis per API 674

API Standard 674 3rd Edition (Dec 2010) defines the pulsation and vibration control requirements for a reciprocating pump. For medium to high power pump applications (>50 kW), the following scope is recommended.

a. **Pulsation Analysis per API 674**
   i. Proven acoustical analysis software is required. The analysis should be based on a Time Domain (TD) solver to ensure sufficient accuracy.
   ii. Evaluate acoustics of the entire piping system and predict pulsations and shaking forces throughout the system versus guidelines. Evaluate pulsation control solutions and recommend a design that is practical for the application.
   iii. Provide the minimum suction pressure required to prevent cavitation based on pulsation amplitudes.
   iv. Perform a mechanical review of the piping system to evaluate pipe runs and support details (clamp design and spacing).
   v. Review the pump base plate design and make recommendations for adding beams or local stiffness.
   vi. Review small diameter branch connections (for example, instrument connections and level gauges) and make recommendations for support or layout changes to minimize failure risk. Recommendations are based on past experience and best practices.

b. **Pump Valve Dynamics: Option** It is recommended to evaluate and, if necessary, adjust the pump's valve dynamics once operational. The information necessary to complete a Valve Dynamic Analysis (VDA) is often not available during the package design stage. A field test has been found to be much more accurate than attempting to model the valve behavior.

c. **Mechanical Analysis**
   i. Prepare a Finite Element Analysis (FEA) of the piping system. Calculate mechanical natural frequencies (MNF) and recommend changes to ensure the MNFs are 20% above the plunger passing frequency. The report shall include a summary of calculated MNFs vs. order of run speed as well as mode shape plots.
   ii. Approved FEA software shall be used for the analysis. The software shall have capabilities to simulate structures using 3D solid and shell elements. Approved software packages include ANSYS, and Nastran. Piping FEA software, such as CAESAR II, AutoPIPE and other similar software programs shall not be approved for this application.

**3. Piping Flexibility (Thermal) Stress Analysis**
**Options: Nozzle Loads, and or Environmental Loads**

a. Applies to large piping systems or where hot liquid is involved.
b. The model shall be terminated either at an anchor point (which must have a stiffness an order of magnitude higher than adjacent supports) or at a point significantly far away from the edge of scope so as to not influence the results.
c. Equipment nozzle loads shall be evaluated against API 610, API 661, or other specifications or field-proven guidelines. Vessel nozzle loads may be evaluated against WRC 107 or other field-proven guidelines.
d. Boundary conditions shall be accurately modeled with appropriate stiffness, gaps, and friction. “Anchor” or “rigid” boundary conditions are typically not appropriate and result in excessively conservative recommendations.
e. Environmental loads shall include effects of wind, seismic movements, snow loads, and other loads appropriate for the particular application.

**4. Base Plate Design**

a. Base Plate Review
   i. A direct and stiff load path from the pump anchor bolts to the foundation shall be ensured. Gussets or proper location of skid beams shall be used to minimize local flexing of beam flanges.
   ii. Concrete within the beams below the pump is generally beneficial to minimize vibration. Nelson Studs or similar shall be used to ensure a mechanical bond between the base plate beams and concrete.
b. Base Plate/Skid Dynamic Analysis for Reciprocating Pumps
   i. ANSYS FEA software shall be used to create and analyze the skid model.
   ii. All forces and couples shall be applied to the model including pump and driver unbalance, forces generated inside reciprocating fluid ends, and significant pulsation forces.
   iii. Skid vibration guidelines shall be based on API 674 or other field-proven guidelines.
   iv. Stress guidelines shall be based on appropriate fatigue failure guidelines.
   v. Report shall include design modifications to meet guideline. Report shall include plots of mode shapes and vibration plots for 1X plunger passing frequency run speeds.
c. **OPTION** Lifting Analysis may be done for new base plate designs. Maximum base plate deflection shall be based on appropriate guidelines. Stress guidelines shall be based on AISC ASD, or other appropriate guidelines. Report shall include design modifications to meet guidelines. Report shall include vibration and stress plots.
d. **OPTION** Transportation and Environmental Loading (including seismic, wind, and wave) as required.

**5. Foundation or Structural Dynamic Analysis**

a. Foundation Design
   i. Foundation dynamic model shall include soil properties from geotechnical report.
   ii. Suitable modeling software shall be used to determine dynamic response characteristics of the load bearing soil structure to create boundary conditions.
   iii. ANSYS FEA software shall be used to accurately model soil dynamic response, foundation model, and skid.
   iv. Assess model flexible modes on the pump skid and provide recommendations to avoid vibration and resonance.
b. Structural Dynamic Analysis required for onshore or offshore platforms and FPSO steel structural applications.

i. A Structural Dynamic Analysis shall include all requirements defined in section 4b above (Skid Dynamic Analysis).
ii. The model shall include enough of the surrounding structure to accurately predict MNFs and vibrations. For floating applications, such as an FPSO, the complete module or topside structure supporting the pump package(s) may need to be modeled. For a fixed structure, such as an offshore platform, the production deck in the area around the package shall be modeled. In some cases, the decks above and below the compressor deck may also need to be modeled.
iii. The effect of vibration of multiple units operating in close proximity shall be considered.

## 6. Torsional Vibration Analysis (TVA)

a. Required for new driver pump combinations, load, or operating conditions on centrifugal and reciprocating pumps.
b. TVA shall include a Forced Response Analysis to ensure torsional shaft stresses and design factors are acceptable with a maximum modal damping of 1%.
c. All anticipated machine operating conditions including start-up, transient, and upset over the full speed range shall be evaluated.
d. The impact of tolerances for all inputs shall be evaluated.
e. Report shall include interference plots, mass-elastic data, torque-effort, stresses, and design factors.

## 7. Small Bore Piping Design Review

a. Small bore piping (PSVs, relief lines, drains, sight glasses, etc. - typically NPS 2 or less) shall be evaluated for risk of fatigue failure.
b. At the design stage small bore piping shall be evaluated for likelihood of failure (LOF).
c. After start-up, a small bore piping vibration audit shall be conducted and compared to field-proven guidelines.
d. Report shall include design of mechanical recommendations to mitigate risk of fatigue failure.

## 8. Water Hammer Transient Analysis

a. Evaluate piping system, layout, and elevations of system components.
b. Transient Analysis of the system shall include pump startups/shutdowns, upset conditions such as power loss, emergency shutdown (ESD) valves, PSVs, block valves, and check valves.
c. Analysis shall include an evaluation of maximum/minimum transient pressures, overpressure, pipe collapse, cavitation, column separation, and check valve slam.
d. Analysis shall include evaluation of block valve trim and closing times.
e. Transient forces on the piping system shall be evaluated against industry force guidelines and, if necessary, included in the Piping Flexibility (Thermal) Stress Analysis.
f. Simulation software to be based on Method of Characteristics.

## 9. Piping Vibration Integrity Study (Plant Wide Assessment)

a. Define the scope of the piping system to be assessed.
b. Identify all major and minor pieces of reciprocating or rotating machinery.
c. Perform a qualitative and quantitative assessment of the required piping system, including pumping systems.
d. Evaluate piping system per the excitation sources specified in the ***Energy Institute Assessment Guideline (2008) for Vibration Induced Fatigue Failure*** guideline.
e. Identify likelihood of failure ratings, recommendations, and proposed modifications.
f. Recommend plan and scope for on-site survey and measurements.
g. Use ***Energy Institute Assessment Guideline (2008) for Vibration Induced Fatigue Failure*** as controlling document.