SPECIFICATION for Pulsation/Vibration Study – Reciprocating Compressors

This specification is made up of two main sections to help you specify an appropriate vibration study. The first, **Steps for a Successful Project**, shows the process and gives a brief explanation of terms. As shown in the chart below, a pulsation/vibration study is made up of several components and these are explained in more detail in the second section, **Study Component Descriptions**.

Steps for Successful Project

The end user or engineering consultant:

1. Determines the APPLICATION RISK based on application and mechanical considerations (very low, low, medium, or high).
2. Using the chart below, identifies the vibration study components required for the application. The components are explained in the second section, Study Component Descriptions.
3. Contracts directly with the vibration consultant to ensure an integrated study, including off-skid and on-skid requirements.
4. Initiates the vibration study early in the process (before initial design layout).

	← APPLICATION RISK →			
Vibration Study Component	**Very Low**	**Low**	**Medium**	**High**
1. Torsional Vibration	**A Torsional Vibration Analysis (TVA) is required if new driver/compressor configuration, change in operating conditions, etc.**			
2. Performance	n/a	**Basic Performance and Pressure Drop Reporting through pulsation control devices (M3)**		
3. Pulsation + Performance	**Bottle Sizing only (M1)**	**Pulsation Analysis (M2)** **(acoustic study of compressor piping system)** **Option: Evaluate off-skid piping**		
4. Mechanical Analysis	n/a	**Review (M4)**	**MNF Analysis (M5)** (frequency avoidance)	**MNF + Forced Response Analysis (M5 – M7)**
5. Skid & Foundation Review	n/a	n/a	**Skid Review**	**Skid Dynamic Analysis;**
		Option: Lifting; and/or Transportation/Environmental Analysis		

Options:	
6. Thermal (Piping Flexibility)	**Recommended if coolers mounted off-skid**
7. Small Bore Piping Vibration	**Review small bore piping analysis /audit**
8. Foundation (or Structural) Dynamics	**Structural Dynamic Analysis required for offshore facilities.** **Foundation design recommended for medium to large units mounted on piles or gravel, and for critical applications.**
9. System Pressure Drop and Performance	**Assess total pressure drop through compressor station (fence to fence) and determine the impact on performance (compared to initial compressor design assumption)**

Note

The "M" nomenclature in the previous chart refers to API 618 vibration requirements. For example:

- M2-M4: basic pulsation study with mechanical review
- M2-M5: basic pulsation and mechanical analysis
- M2-M7: pulsation with advanced mechanical analysis (forced response)

Other options are available, but seldom required. Contact us for more information.

Terms

- **Torsional Vibration Analysis (TVA)** Evaluate torsional system and provide recommendations to avoid resonance and ensure torsional stress is below guideline.
- **Compressor Performance Assessment** For overall operating map, assess the performance impact and pressure drop due to pulsation control only, or including piping, coolers, vessels, etc.
- **Pulsation Analysis** Perform an acoustic simulation of the piping system and recommend a pulsation control solution.
- **Mechanical Review** Basic review of piping system using standard "rules of thumb." Does not include Finite Element (FE) modelling.
- **Frequency Avoidance Analysis** Using an accurate FE model, assess pulsation forces and gas forces across the relevant harmonics to avoid resonance conditions.
- **Forced Response Analysis** Using an accurate FE model and significant forces, calculate vibration and stress amplitudes. Recommend modifications where stress exceeds guideline.

Study Component Descriptions

1. **Torsional Vibration Analysis (TVA)** shall be done for any new driver/reciprocating load combination.
    a. TVA shall include a forced response analysis to ensure torsional shaft stresses and design factors are acceptable with a maximum modal damping of 1%.
    b. All anticipated machine operating conditions, including start-up, transient, upset, conditions over the full speed range shall be evaluated.
    c. Compressor unloading shall be investigated.
    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.

2. **Compressor Performance and Impact of Pressure Drop**
    a. Operating conditions used in pulsation and performance analysis shall include the full operating envelope based on the range of pressures, temperatures, specific gravities, cylinder clearances, valve unloading, and compression ratios. Evaluating only a few conditions is not sufficient.
    b. The impact on capacity and load (performance) due to pulsations and pulsation control shall be evaluated and included in the report.
    c. Static and total pressure drop (static+dynamic) shall be reported and compared to API 618, 5th Edition guideline when designing pulsation control devices.
    d. **<u>Option:</u> System Pressure Drop and System Performance** Total pressure drop from station inlet to outlet ("system pressure drop") shall be evaluated and reported. The compressor performance shall be re-calculated based on system pressure drop ("system performance").

3. **Pulsation**
   a. **Bottle Sizing** – calculate pulsation bottle sizes and internal filter elements using a mini-pulsation study.
   b. **Pulsation Analysis**
      i. **on-skid piping**
         - Software shall calculate pressure pulsations and pulsation-induced unbalanced forces (“pulsation forces”), up to a minimum frequency of 150 Hz.
         - Software shall be capable of including non-linear fluid dynamics and time-varying boundary conditions. Programs based solely on acoustical theory are not sufficient.
         - Pulsation guideline shall be based on API 618, 5th Edition or other field-proven guidelines.
         - Pulsation force guidelines for piping and vessels shall be based on API 618, 5th Edition or other field-proven guidelines.
         - Pulsation forces between the compressor cylinder and pulsation bottles shall be calculated and evaluated using field-proven guidelines.
         - Report shall include design of pulsation control devices (e.g., pulsation bottles, restrictive orifice plates, line reductions) to meet guidelines. Report shall include plots of pulsations and pulsation forces compared to guideline.
      ii. **off-skid piping** The pulsation study shall include off-skid piping, if available, when multiple units are connected or when coolers and/or scrubbers are not part of the compressor package. The extent of the off-skid piping model typically includes piping up to a large vessel or mainline connection.

4. **Mechanical Analysis**
   a. **Mechanical Review** Piping, vessels, and vessel small-bore connections shall be reviewed before compressor package drawings are released for construction.
   b. **Frequency Avoidance Analysis**
      i. Significant forces shall be calculated, up to a frequency of 150 Hz, and reported, including:
         - Pulsation Forces (those forces described in 3a that exceed guidelines)
         - Cylinder Gas Forces (also called cylinder stretch forces). This includes forces that exceed the following guideline:
            - The maximum cylinder gas force at 1X compressor runspeed shall be less than 100% of rated rod load (tension or compression, whichever is lesser).
            - The maximum cylinder gas force at orders greater than 1X compressor runspeed shall be less than 10% of rated rod load (tension or compression, whichever is lesser).
      ii. Finite Element Analysis (FEA) models shall be used to calculate mechanical natural frequencies (MNFs) and mode shapes.
      iii. The calculated MNFs shall meet the API 618, 5th Edition guideline, listed below.
         - MNFs shall have a 20% separation margin from 1X and 2X compressor runspeeds.
         - MNFs shall have a 20% separation margin from other orders that have significant forces (identified in 4.b.i).
      iv. Finite Element models shall include rotational inertia of elements. Some piping FEA programs do not have this capability and shall not be used for this analysis.
      v. Complex geometries (like vessel nozzles, scrubber base supports, and cylinder distance piece supports) shall be modelled accurately using shell or solid elements. Alternately, a representative stiffness can be calculated to approximate complex geometries.
      vi. Boundary conditions (such as scrubber base connections and distance piece connections) shall be accurately modelled with appropriate stiffness. “Anchor” or “rigid” boundary conditions for vessels are unacceptable.

vii. The calculated weights of vessels in the mechanical model shall be compared to customer information. Discrepancies shall be documented.
viii. Report shall include designs of the mechanical recommendations required to meet guidelines. Report shall include plots of mode shapes and MNFs.
ix. A Forced Response Analysis shall be done, using significant forces, if mechanical recommendations to meet MNF guideline cannot be implemented.

c. **Frequency Avoidance + Forced Response Analysis**
i. A Forced Response Analysis shall include all requirements defined in section 4.b. above.
ii. The compressor manifold shall be modelled (compressor cylinder assembly, pulsation bottles with associated piping and other process vessels).
iii. All forces shall be applied to the model, including cylinder gas forces, crosshead guide forces, and pulsation forces. The full range of operating conditions shall be considered to determine the worst case forces.
iv. A maximum damping ratio of 1% shall be used unless field measurements have been taken.
v. Vibration guidelines shall be based on API 618, 5th Edition or other field-proven guidelines.
vi. Stress guidelines shall be based on API 618, 5th Edition (with appropriate stress concentration factors), or other field-proven guidelines.
vii. Report shall include design of mechanical recommendations to meet vibration and stress guidelines. Report shall include vibration and stress plots.
viii. **OPTION: Piping Forced Response Analysis** Forced Response Analysis of piping away from compressor manifold shall be done if the pulsation force guideline cannot be met, or the Frequency Avoidance Analysis recommendations cannot be implemented.

5. Skid

a. **Skid Review**
i. A direct and stiff load path from the compressor 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. Avoid using beams less than 18" tall for compressor and engine pony skid unless detailed Finite Element Analysis is done.
iii. Concrete in the skid below the compressor is generally beneficial to minimize vibration. Nelson Studs, or similar, shall be used to ensure a mechanical bond between the compressor skid and concrete.
iv. Epoxy grout is recommended for shimming between the compressor skid and concrete foundation.
v. If the compressor application is onshore using steel piles, piles shall be installed below the compressor crankcase as well as the crosshead guide support. Piles shall be used below the compressor cylinder head end if support is required.
vi. Three point mount for compressor skid shall not be used for offshore application. Skids shall be well supported under the compressor frame, driver, and large vessels. A Forced Response Analysis of the compressor package and offshore structure shall be done.

b. **Skid Dynamic Analysis**
i. All forces and couples shall be applied to the model, including compressor and driver unbalance, cylinder gas forces, crosshead forces, and significant pulsation forces.
ii. Skid vibration guidelines shall be based on API 618 5th Edition or other field-proven guidelines.
iii. Stress guidelines shall be based on appropriate fatigue failure guidelines.
iv. Report shall include design modifications to meet guideline. Report shall include plots of mode shapes and vibration plots for 1X and 2X compressor run speeds

c. **OPTION: Lifting Analysis** A lifting analysis may be done for new skid designs. Maximum skid 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.

6. **Thermal (Piping Flexibility) Analysis**
   i. The main discharge process piping, between the compressor and the cooler, shall be analyzed. Other main process piping may be analyzed.
   ii. The model shall be terminated either at an anchor point (which must have a stiffness and 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.
   iii. Cooler nozzle loads shall be evaluated against API 661, or other field-proven guidelines. Vessel nozzle loads may be evaluated against WRC 107, or other field-proven guidelines.
   iv. Boundary conditions shall be accurately modelled with appropriate stiffness, gaps, and friction. “Anchor” or “rigid” boundary conditions are typically not appropriate and result in excessively conservative recommendations.

7. **Small Bore Piping Audit**
   Small bore piping is not typically addressed in a standard pulsation/vibration study and can represent a high risk of fatigue failure.
   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. **Foundation (or Structure) Dynamic Analysis**
   Not typically within packager scope but may significantly affect on-skid vibration levels. Especially important in offshore applications.
   a. Foundation Dynamic Analysis
      i. A Foundation Dynamic Analysis shall consider geotechnical data describing soil dynamic properties.
      ii. Software shall accurately predict vibration due to dynamic loads, shall account for frequency dependent stiffness and damping of piles, shall account for multi-layer solids, piles interaction, and foundation embedment.
   b. Structural Dynamic Analysis:
      i. A Structural Dynamic Analysis shall include all requirements defined in section 5.b above (Skid Dynamic Analysis).
      ii. The model shall include enough of the structural supporting to accurately predict MNFs and vibrations. For floating applications such as an FPSO, the complete module or topside structure supporting the compressor package(s) may need to be modelled. For a fixed structure, such as an offshore platform, the production deck in the area around the package shall be modelled. In some cases, the decks above and below the compressor deck may also need to be modelled.
      iii. The affect on vibration of multiple units operating in close proximity shall be considered.
      iv. **OPTION: Test Structural MNFs** Impact, shaker, or run tests shall be conducted on the compressor package during construction in the shipyard to confirm dynamic analysis.