SPECIFICATION for Reciprocating Compressor
Pulsation and Mechanical Vibration Analysis

This specification is to help owners and EPCs specify the appropriate vibration study scope for a reciprocating compressor. The specification is based on these requirements:

- API 618 (latest revision), relating to pulsation studies
- GMRC High Speed Compressor Guideline, 2013
- Energy Institute guidelines for the avoidance of vibration induced fatigue failure in process pipework, Jan 2008 (applicable to main piping, and small bore piping vibration)
- Dynamics studies for foundation, skid and offshore facilities (application specific)

Steps for Successful Project

1. Determine the study requirements based on the risk factors and application (refer to table on our website: BetaMachinery.com > Reciprocating Compressors > Design Requirements)
2. Ensure an integrated approach to vibration mitigation. This means the scope includes on-skid design (compressor package), off-skid piping requirements, foundation/support design, and pipe stress analysis.
3. Engage the pulsation or vibration consulting engineer early in the process (before initial design layout is completed). Often the end user or EPC will engage this expert directly to ensure an integrated approach.

Contact Beta Machinery Analysis for application questions relating to vibration mitigation studies.

Pulsation/Vibration Study Requirements

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. Address torsional to lateral vibration (torsional impact on mechanical design)
    f. 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.

3. **Pulsation**
   a. **Bottle Sizing** – calculate pulsation bottle sizes and internal filter elements using a mini-pulsation study.
   b. **Pulsation Analysis (M2 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 (M4 Analysis)**
   b. Piping, vessels, and vessel small-bore connections shall be reviewed before compressor package drawings are released for construction.
   c. **Frequency Avoidance Analysis (M5 Analysis)**
      i. Significant forces shall be calculated, up to a frequency of 150 Hz, and reported, including:
         - Pulsation Forces (those forces described in 3b 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 run speeds.
         - 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.

d. **Frequency Avoidance + Forced Response Analysis (M6 and M7 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. **<u>OPTION:</u> 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. **<u>OPTION:</u> 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. **<u>OPTION:</u> Transportation and Environmental Loading** (including seismic, wind, and wave) as required.

6. **Piping Stress Analysis (Thermal/Piping Flexibility Analysis)**
   a. The main discharge process piping, between the compressor and the cooler, shall be analyzed. Other main process piping may be analyzed.
   b. 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.
   c. 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.
   d. 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**
   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**
   Although not typically within packager scope, this may significantly affect on-skid vibration levels.
   a. Foundation Dynamic Analysis (land based)
      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 (offshore based):
      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 modeled.
      iii. The effect on vibration of multiple units operating in close proximity shall be considered.