Specification:
Vibration Studies for Reciprocating Compressors
Design Approach 3 (per API 618, 5th edition)

***SCOPE**: The specification includes a pulsation and mechanical analysis (Part A, 1.0). The other studies outlined in this specification may be required as well. The customer shall select the appropriate scope.*

***INSTRUCTION**: The owner or its designated representative shall issue this specification as part of the compressor design requirement, or directly to the approved Vibration Consultant.*

Part A: Compressor Package

1. **Design Approach 3: Pulsation (Acoustical) and Mechanical Vibration Analysis** per API 618 (5th edition) including Steps 3a and 3b.

   (i) Pulsation (acoustic) analysis:

   a. Non-linear Time Domain software shall be used.
   b. Commercial software that is based on Frequency Domain algorithms is not acceptable.
   c. MAPAK software is an approved non-linear Time Domain solver for acoustical studies (version 23 or higher).
   d. The study shall include an analysis of the following factors for all operating conditions specified, and for all locations in the piping system (including off-skid piping if required):
      - pressure pulsations vs guideline;
      - unbalanced pulsation shaking forces vs guideline;
      - static and total pressure drop vs guideline;
      - meter error if required, and
      - other deliverables specified in the Standard.
   e. A performance analysis shall be completed for the compressor package, and include:
      - pulsation effect on compressor performance;
      - calculated power, capacity, efficiency, rod loading, and gas forces for all conditions; and
      - effect of total pressure drop on compressor power.
   f. Piping Restraint Analysis shall utilize a table of the maximum allowable span between piping supports as a function of pipe size. This analysis shall also include a review of the system to ensure the mechanical design follows good design practices.
   g. Option: Provide a system performance report of the unit including all operating conditions for the entire package (including piping, coolers, vessels, pulsation control, etc). Compare performance to initial specification to identify potential performance gaps.

   (ii) Mechanical Vibration Analysis:

   a. Approved FEA Software. Finite Element Analysis (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 are such as ANSYS, Nastran and Cosmos. Piping Finite Element Analysis Software programs such as CAESAR II, Autopipe and other similar software programs shall not be approved for this application.
   b. Modeling Accuracy. Precise modeling techniques are required to accurate predict boundary condition and the resulting MNFs. The following methodology is required:
      - Provide evidence that the FEA modeling technique employed by the consultant will achieve <10% variance between calculated and field-measured MNFs. Provide evidence that mechanical modeling techniques are continually field tested.

- Utilize shell or solid element types to model vessel nozzles and repad details. Beam element models are not acceptable.
- Utilize shell or solid element types to model scrubber bases and pipe support to determine boundary condition.
- Utilize full frame compressor model, or field verified boundary condition stiffness at the crosshead guide-frame boundary.
- Verify that the weights of the vessels used in mechanical models match the weights in the customer drawings

Step 3a: Calculate Mechanical Natural Frequencies (MNF) and Avoid Resonance

a. The report shall include a summary of calculated MNFs vs order of run speed as well as mode shape plots.
b. The report shall include recommendations to achieve these goals:
    - Avoid resonance at 1X and 2X (goal is to move MNF > 2.4 run speed for variable speed machines)
    - 20% separation margin from significant excitation frequencies for other orders
c. Calculate and report the amplitude and frequency of cylinder gas forces for all operating conditions for at least the first 20 orders of compressor speed. A limited forced response is to be completed for the following situations:
    - If a cylinder gas force at a particular order exceeds 10% of the rated rod load –for single cylinder nozzle bottle or if multiple cylinders are out of phase
    - If a cylinder gas force is greater than 5% of the rated rod load for multiple cylinder pulsation bottles where the cylinder phasing corresponds to the mode shape of the pulsation bottle
    - The limited forced response analysis includes calculating the vibration and dynamic stress due to the compressor cylinder gas forces only.

Step 3b: Forced Response Analysis to Calculate Vibration and Dynamic Stress Levels

a. Step 3b.1: Include the Forced Response Analysis in original project scope if the rod load exceeds 80% rated and/or HP/Cylinder exceeds 700 (520 kW/cylinder). The analysis is also required after the Step 3a analysis has been completed if
    - separation margin criterion cannot be met
    - pulsation forces in the bottles exceed guideline, or
    - cylinder gas forces or bottle mode shapes exceed levels described section 1.ii.e
    - The scope of the analysis is limited to the compressor manifold, that is the compressor cylinder assembly, pulsation bottles with associated piping and other process vessels.
    - Include cylinder gas forces (cylinder stretch), pulsation forces, and crosshead forces for the range of operating conditions that capture the highest force amplitudes.
    - Calculate vibration and stress amplitudes for all nodes in the system and for orders of run speed above 2X.
b. Step 3b.2: Assess piping and vessels away from the immediate compressor vicinity when the shaking force guidelines cannot be met, or the piping restraint analysis recommendations cannot be implemented.
c. Recommend improvements to the mechanical design to meet the design guidelines.
d. Report to include calculated MNFs, vibration and stress levels.
e. Option for superior accuracy of Forced Response Analysis (to be confirmed by customer). The mechanical analysis shall include a FEA solid model of the compressor frame, compressor pedestal, compressor skid and foundation.

Alternate software for pulsation analysis (1.(i).b) or mechanical analysis (1.(ii).a) must be pre-approved by owner prior to bidding project.

2. Torsional Vibration Analysis (TVA)

a. Torsional analysis shall include the full drive train (e.g., compressor, coupling, gearbox, and driver).
b. A forced response analysis shall be conducted to ensure torsional shaft stresses and design factors are acceptable for all critical shaft elements.
c. A complete range of anticipated machine operating conditions, including start-up, transient, and steady state over the full speed range should be considered. Compressor unloading should be investigated.
d. Upset conditions shall also be investigated.
e. A tolerance band analysis shall be employed (eg. investigate tolerances of all model inputs). The analysis shall predict and report a range of predicted natural frequencies and design results to ensure safe and reliable machinery operation.

3. Piping System Flexibility (Thermal) Analysis （As Required)

a. The scope will include analysis of the piping, vessels, coolers and other equipment within the package limits and extending out into the station piping to the extent that is necessary to accurately simulate the response of the system.
b. All pipe restraints and boundary conditions shall include an appropriate flexibility. Assuming rigid boundary conditions at all pipe restraints shall not be done as this will result in an overly conservative flexibility design.
c. To minimize the number of piping and support design iterations, the piping system flexibility and stress analysis shall be performed by the same consultant performing the API 618 mechanical studies.

4. Skid Lifting and Loading Study (As Required)

a. The lifting analysis includes evaluating a finite element model of the skid to ensure the skid member stresses and deflections are within allowable levels. If required, this analysis includes design and evaluation of spreader bar, slings and shackles for lifting the skid.
b. Additional scope to the Skid Design Review and Lifting Analysis service includes checking the structure for stresses and deflections due to Environmental Loading such as transportation, seismic, and/or wind loads.

5. Skid Dynamic Analysis (As Required)

a. Calculate skid vibration and stress, and compare to industry or customer guideline.
b. Define magnitude and frequency of dynamic loading on the skid. For reciprocating compressors, the dynamic loads include unbalanced forces and moments, cross-head guide forces, gas rod load forces, acoustical forces in piping and vessel, and unbalanced forces and moments in the driver.
c. Consider boundary conditions from the foundation (pile, gravel pad, concrete block or steel structure).

6. Small Bore Attachments

a. The consultant to provide recommendations with regard to small bore piping based on good design practices.

7. Packager Shop Visit:

a. Collect Mechanical Natural Frequencies (MNFs) for vessels, bottles, frame, piping, and small bore attachments.

b. Identify locations where resonance is likely, and recommend changes to the design.
c. Review piping layout, clamps, supports and other package layout to ensure study recommendations and good design practices has been implemented.

Part B: Dynamic Analysis of Foundation or Structure (Offshore Applications)

Part B involves close co-operation with the Engineering Consultant and end user. The purpose of this analysis is to evaluate the response of the compressor skid and its support structure due to dynamic equipment loads. The following requirements to be performed by the same consultant who will perform the compressor vibration analysis included in Part A.

1. Foundation Applications

a. Customer to specify foundation type (i.e., concrete block, gravel pads, piles, table top, and hybrid using concrete and piles).
b. Identify dynamic loads and consider soil – structure interaction effects under such loads.
c. Customer to provide local geotechnical report that identifies local soil conditions.
d. Assess the foundation's natural frequency, damping, resonance and the impact on vibration.
e. Calculate dynamic response due to foundation MNF and dynamic forces in the machinery
f. Provides recommended foundation design to limit vibration to safe levels

2. Dynamic Structural Analysis for Offshore Platforms/FPSOs

a. The analysis will include evaluation of a finite element model of the skid and support structure (eg. the platform deck on a fixed offshore platform or the topside structure of an FPSO application).
b. This analysis calculates the structural response due to dynamic loads from the machinery mounted on the skid. This analysis involves creating and analyzing a detailed beam, plate and brick finite element model of the skid, compressor frame and other significant components. Machinery loads and acoustical loads are applied to calculate the vibration of the system and determine modification that will ensure the response is within industry standard guidelines.
c. The dynamic loads for the reciprocating compressor package(s) includes unbalanced forces and moments in the reciprocating compressor, compressor cross-head guide forces, gas rod load forces, acoustical forces in piping and vessel, and unbalanced forces in the driver.

Part C: Condition and Performance Monitoring

Contact Beta Machinery Analysis for recommendations on sensors, data, control system, vibration and other requirements necessary to support a condition and performance monitoring programs.

Part D: Field Visit to Measure Vibration Baseline

a. Inspect installation to ensure study recommendations have been implemented.
b. Site visit to measure pulsation and vibration on compressor, piping, driver, skid, platform or module, and selected small bore attachments.
c. Measure vibration and pulsation levels across entire speed range.
d. Measure vibration on each reciprocating machine.
e. Assess vibration due to the interaction of multiple machines.
f. Prepare an Operated Deflected Shape analysis for the subject equipment/platform.
g. Compare vibration to industry accepted guideline. Identify locations/frequencies where vibration exceeds guideline.
h. Summarize baseline results and provide recommendations.