Get the Best Possible Design for your Reciprocating Compressor Package

PRIMER
Vibration Control Strategies for Reciprocating Compressors

Beta Machinery Analysis

Consumers are statistics. Customers are people. *Stanley Marcus*

It is to our customers that this Primer is dedicated.

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Introduction

This primer describes the scope and methodology to mitigate pulsation and vibration on the compressor/driver, piping, vessels, skid, and foundation. Since the pulsation control solution affects overall compressor performance, a discussion on compressor performance is also included.

A reciprocating compressor generates pulsations due to the motion of the piston pushing gas through the system. The reciprocating (and rotating) action also generates other dynamic forces on the system. If not addressed properly, these forces can generate excessive vibration. The same principles apply to reciprocating pumps. Industry studies show that vibration is the leading cause of mechanical problems on these machines.

Vibration problems are very costly to owners – especially when including the downtime and repair costs. The best, and most cost-effective, approach to avoid problems is to modify the package during the design stage. Simple changes can be made to the package, including altering the pulsation bottle design, piping arrangement, and supports. These low cost modifications avoid costly problems later.

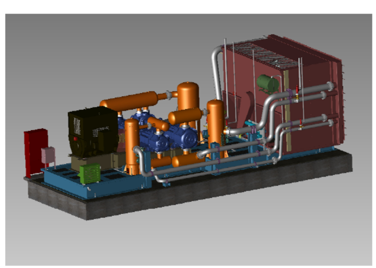
A pulsation/vibration study is routinely performed on new projects, or when existing compressors are going to be modified to run at different conditions. API 618, 5th edition, specifies vibration control strategies for the compressor package. This primer explains how to apply API 618 and what specifications are important in a vibration study.

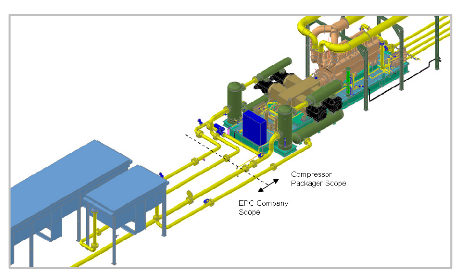
These issues directly relate to the specifications and design processes undertaken by EPCs, compressor packagers, and owners (including facility engineers, rotating engineers, and other employees directly affected by the design or modification of compressors).

Depending on the application, the study may include one or all of these elements:

- Pressure pulsations in the piping system;
- Mechanical resonance and vibration in the piping system, scrubbers, bottles, frame, driver, small diameter instrumentation lines, or other components;
- Torsional vibration in the drive train;
- Movement and resonance in the foundation and skid;
- Thermally induced stress; and
- Performance degradation or inefficiency due to excessive pulsation and/or pressure drop.

The owner is responsible for specifying the design requirements that result in an efficient, reliable and safe compressor system. Unless specified, the appropriate design study will not be included. A standard specification for these studies is available on our web site, www.BetaMachinery.com.





Vibration design studies are routinely performed on compressor packages over 400 HP.
Owners and EPCs are responsible for specifying the appropriate study scope.

Included

Chapter 1 outlines the strategies to avoid vibration, applicable Standards, and available design options. It summarizes the performance related issues that can affect compressor operation and provides tips for a successful study and installation.

Chapter 2 describes the scope, deliverables, and methodology for controlling pulsations and their resulting forces. This step is based on the most recent API 618 Standard (5th edition). A pulsation study (or acoustical analysis) simulates the piping system to assess pressure pulsations under all operating conditions and accurately calculate the impact of the proposed pulsation control solution.

Chapter 3 describes the scope, deliverables and methodology for the mechanical vibration analysis. This study can range from a simple mechanical review to a detailed Finite Element Analysis (FEA) model that can accurately predict vibration and stress.

Chapter 4 explains the concept of system performance and how this affects throughput and efficiency, and outlines a new approach for optimizing the design for compressor stations.

Chapter 5 summarizes the key points in the primer.

Note: Contact BETA, info@BetaMachinery.com, for a detailed discussion of technical guidelines and methodology. We encourage questions or comments on this technical primer, and welcome suggestions for improvement by the industry.

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Beta Machinery Analysis is a global leader in machinery design for reciprocating and rotating machinery and associated equipment, solving vibration and pulsation issues for both on and off shore applications.

1. Vibration Control Strategy

1.1. Background

Dynamic Forces

Reciprocating compressors (and pumps) generate high dynamic forces. These forces are due to the inertia of the piston and other reciprocating and rotating components, gas and liquid forces, and pulsation pressure induced forces in piping (Figure 1.1).

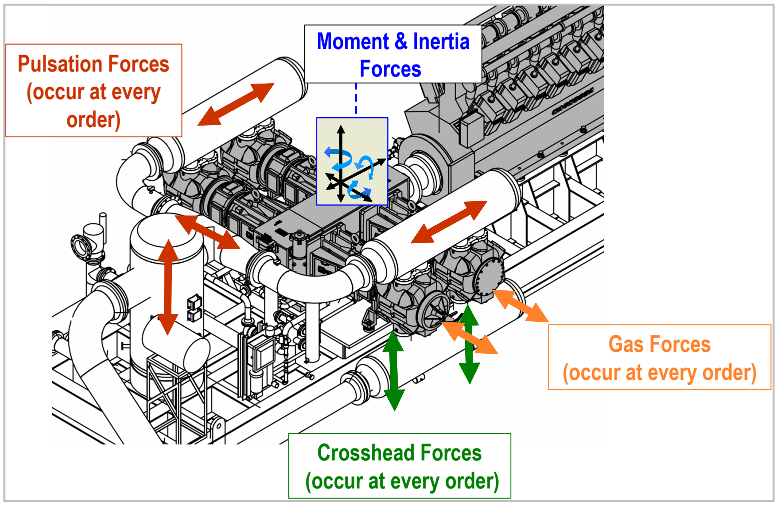


Figure 1.1: Dynamic Forces Affecting Compressor

Dynamic forces are complex waveforms that can be represented by a series of vectors at multiples of the fundamental frequency (harmonics). A spectrum of a typical force is shown in the chart, Figure 1.2. For example, a compressor running at 1200 RPM (or 20 Hz), generates forces at the first order of run speed (referred as 1X, or 20 Hz). It also contains force amplitude at 2X (40 Hz), 3X (60 Hz), etc., as illustrated below. The highest forces are usually at 1X and 2X, but other forces need to be considered as well.

Vibration and Stress Limits

These dynamic forces cause the piping system and vessels to vibrate. Unless vibrations are controlled, components will fail due to excessive stress (see Figure 1.3). Even if components do not fail, the result of excessive vibration is increased maintenance cost (and associated downtime) due to operating problems.

To ensure vibration and stress are within acceptable limits, an appropriate design study is needed, such as the BETA Design Study. The objective of a BETA Design Study is to ensure vibration and stress are below industry guidelines.

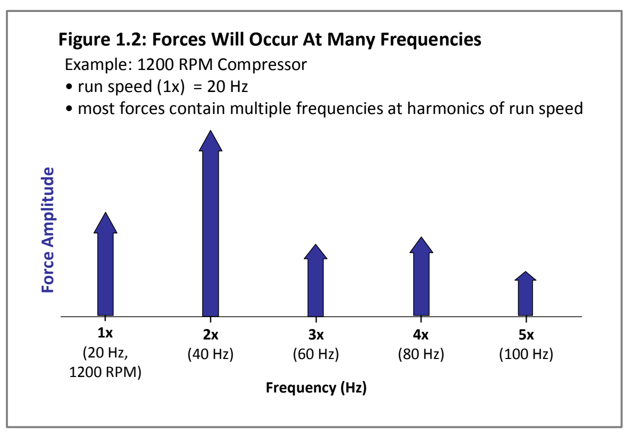


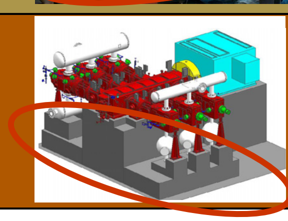
Figure 1.2: Dynamic Forces Contain Harmonic Frequencies

Compressors Generate DYNAMIC FORCES:	→	VIBRATION	→	STRESS	→	FATIGUE FAILURE
- pulsation forces - gas forces - crosshead forces - inertia forces & couples		- In horizontal, axial, vertical direction - Across wide frequency range (typically up to 10 X run speed) - Occurs on compressor, piping, vessels, skid, foundation		dynamic stress in vessels and piping		(if stess > allowable)

Figure 1.3: Vibration is The Leading Cause of Compressor Downtime
(Due to excessive stress on components)

An Integrated Solution is Necessary

The entire system; compressor, piping, skid and foundation must be designed to support the dynamic loads. If one element is incorrectly designed or installed, then excessive vibration will occur. The vibration solution must be integrated across the entire system to ensure adequate dynamic stiffness from the point of load application, through the supports and foundation (as shown below, Figure 1.4)

Compressor & Piping		**API 618 (5th edition): see comments below** • Pulsation (acoustical) solution • Mechanical vibration design • Torsional vibration analysis
Skid Design for Dynamic Loads		**Static skid design** - lifting analysis; transportation; wind, seismic, etc. **Dynamic skid design**: assess dynamic forces, MNF, resonance, stiffness
Foundation (or Offshore Structural) Dynamic Design		**Dynamic vibration analysis:** assess dynamic forces, MNF, resonance, damping, vibration amplitudes, stress

There is a strong dependency between these different engineering activities

Figure 1.4: Integrated Vibration Design

The packager (or fabricator) is responsible for the compressor and skid. The foundation (or offshore structure) dynamic analysis is not included in the packager's scope, and needs to be specified and coordinated by the Engineering Consultant/Owner to ensure it gets done.

As illustrated in Figure 1.4, there are various elements to the compressor system analysis. Depending on the required scope, the study will include one or all of these tasks to ensure an integrated vibration solution.

Approaches to Control Vibration:

Vibration is generated by high forces or when the design has insufficient stiffness (i.e., it is too flexible). The following vibration equation illustrates the relationship between dynamic force, and stiffness.

$$\textbf{Vibration} = \frac{\textbf{Dynamic Forces}}{\textbf{Dynamic Stiffness}} \quad \textbf{or} \quad \textbf{Vibration} = \textbf{Dynamic Forces x Dynamic Flexibility}$$

[note: stiffness = 1/flexibility]

There are two approaches used to control vibration:

i. The pulsation analysis deals with controlling the level of pulsation forces entering the system (note: other dynamic forces can't be reduced). This approach will provide a recommend pulsation control solution (see chapter 2).

ii. The mechanical analysis deals with controlling the responsiveness. This approach will maximize the stiffness of the piping system (or minimize flexibility) to ensure low vibrations. This approach will provide recommendations to the compressor layout and design (see chapter 3).

Good engineering determines the proper balance between these approaches. This includes consideration of costs (bottle sizes, beam sizes, etc), degree of vibration risk, customers design preferences, operational considerations, etc.

API 618 Guidelines for Pulsation/Vibration Studies

API 618, 5th ed., has a detailed section outlining the requirements for pulsation and mechanical vibration analysis. For owners who are buying a new compressor package (or modifying an existing one), this section of the API 618 is used to specify the required compressor vibration study, and to ensure the guidelines are implemented correctly. The vibration standard is used globally for both API, and non-API machines, and is the only applicable guideline/methodology available to industry. We understand that the future versions of API 618 will be harmonized with ISO standards.

The API 618 specification, including the pulsation/vibration requirements, generally focuses on slow and medium speed machines (and fixed speed applications). The specification is now used for high speed machines (greater that 750 RPM), and for applications operating over wide speed ranges.

There are important limitations when applying the vibration specifications of API 618 to high speed machines. The limitations are discussed in Section 3.0.

A risk assessment determines which Design Approach is required (per API 618, 5th Edition). Figure 1.5 illustrates how risk is related to the design study scope for the compressor and piping system.

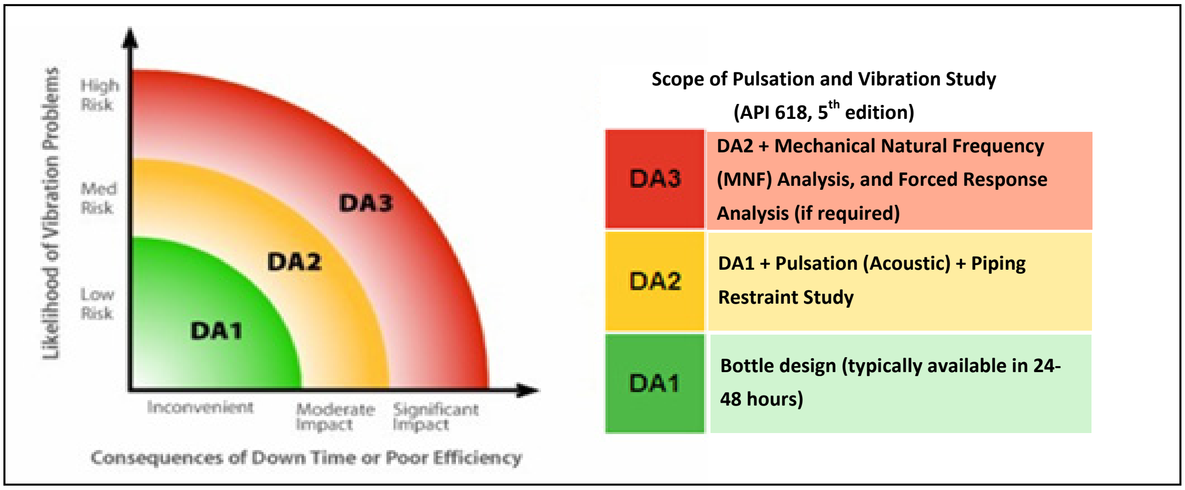


Figure 1.5: Risk Assessment Used to Determine Vibration Design Approach (DA) for the Compressor and Piping System

BETA has a more comprehensive risk rating chart to quantify the risk assessment and can be completed in 5 minutes. Visit our web site or contact us for a copy of this chart, or for application questions.

1.2. BETA Design Study

The following is brief summary of other design study options often included in a compressor project. Contact BETA or visit our website for more application information.

- **Select the appropriate pulsation or mechanical analysis (DA1, DA2 or DA3)** – per figure 1.5. For a DA3 study, a Forced Response Study to calculate vibration and stress amplitudes.

- **Torsional vibration analysis (TVA)** is typically required for any new driver/reciprocating load combination. The torsional analysis involves designing the system to avoid costly torsional failures and ensures safe operation of the compressor and driver. Typically, recommendations from the torsional study include coupling selection, flywheel sizing, driver shaft design, or compressor cylinder loading changes.

- **Piping System Stress/Flexibility (Thermal) Analysis** predicts the cooler nozzle loads and piping stresses resulting from thermal cycles, pipe and fitting weights, static pressure, and bolt-up strains. A thermal analysis will reduce the risk of excessive nozzle load or pipe strain. The scope typically includes the discharge piping between compressors and coolers.

  Note: In the piping design, when clamps are used to avoid mechanical resonances, the thermal flexibility effects should also be considered.

- **Skid analysis** will be required if a new or modified skid design is part of the package or proven skid used in a new application. Skid Analysis investigates skid stresses due to lifting, transportation, seismic loads, and other quasi-static forces. In some cases the scope will be focused on a dynamic vibration analysis of the skid members based on compressor and driver forces. The purpose is to optimize the skid design (lower costs) while ensuring sufficient static and dynamic stiffness.

- **Foundation/Offshore Structural Vibration Analysis** is often required. This scope may be issued directly from the Consulting Engineer (not part of packager scope). Dynamic vibration analysis is commonly included to avoid resonance problems on the foundation or offshore platform/FPSO. This should include the major equipment (e.g., compressor, driver, scrubbers, bottles), dynamic forces, skid and supporting structure and provides recommendations on the foundation or structural design.

- **Compressor Station Performance and Optimization**
  Many customers require accurate performance data for the entire compressor system (including piping, vessels, cooler, pulsation bottles, etc.). This study accurately predicts the power, capacity, system pressure drop and other performance factors, and compares the results to the original specification. The model can be used to optimize the design and recommend changes to increase throughput and reduce losses. Incremental throughput will result in significant payback to the owner (see Section 4.0.) .

- **Field Baseline Vibration Check**
  A vibration baseline should be performed at, or soon after start-up. The objective of the check is to confirm that recommendations have been correctly implemented, and to ensure running vibration and pulsation levels are acceptable. *It is also recommended to <u>check vibration on small bore piping and instrumentation lines</u>.* These lines are not addressed in the standard pulsation/vibration study.
  An optional performance check of new units will verify loading curves, examine valve behavior, optimize valve lift, and determine baseline performance data.

- **Miscellaneous Studies**
  <u>Dynamic and Static Stress Calculation on Pulsation Bottle Internals</u>. This study applies pulsation-induced shaking forces and pressure-induced static forces to the shell and vessel internals and computes stress levels to satisfy API 618. Stress calculations of bottle internals, will ensure long term reliability of important components hidden from view.

  <u>Compressor Valve Dynamic Response Study</u>. This study calculates the dynamic response of the valve spring and sealing elements.

1.3. Tips for a Successful Project

- **Coordination:** A successful compressor vibration solution involves different stakeholders. While the packager has responsibility for the piping and compressor, the owner, or its Engineering Consultant, have responsibility for the foundation or structural design. We recommend the owner/EPC be involved in the reviewing the vibration study and the implications to reliability (vibration risk) and performance.
- **Analysis of all the required operating conditions.** If the speed, gas composition, pressures, loading conditions and/or temperatures change from the initial design, then the vibration solution will be compromised. Care should be taken to ensure all current and future conditions are properly defined.
- **Opportunity to improve efficiency and performance.** Many projects are based on lowest capital cost, and thus reliability and efficiency considerations are secondary. A new approach called “system performance modeling” is available to improve life cycle economics, performance, and reliability.
- **Dynamic analysis of the foundation (or offshore structure).** This analysis is linked to the mechanical vibration design, and typically performed by the vibration consultant. Often this dynamic analysis is omitted, or not coordinated with the package design.

- **Vibration Field Check.** A baseline vibration survey is commonly conducted once the unit is operating in the field. Scope to include small bore piping (which is not evaluated in detail in the design stage). Site survey will identify any remaining vibration issues.
- **Early involvement by Vibration Consultant.** Key aspects of the vibration solution are determined early in the project design process. Costly changes can be avoided if the vibration consultant (BETA) is involved in preliminary design discussions.

2. Pulsation Control (Acoustical Analysis)

2.1. Overview

The goal of this analysis is to design a pulsation control solution that minimizes pulsation related shaking forces while maintaining maximum operational performance. Some people refer to this study as an acoustic analysis. Figure 2.1 illustrates that pulsation forces can reach significant magnitudes, and unless attenuated, will result in piping failures. [Note that all other dynamic forces such as cylinder gas forces or crosshead forces have to be managed by the mechanical vibration design discussed in section 3.]

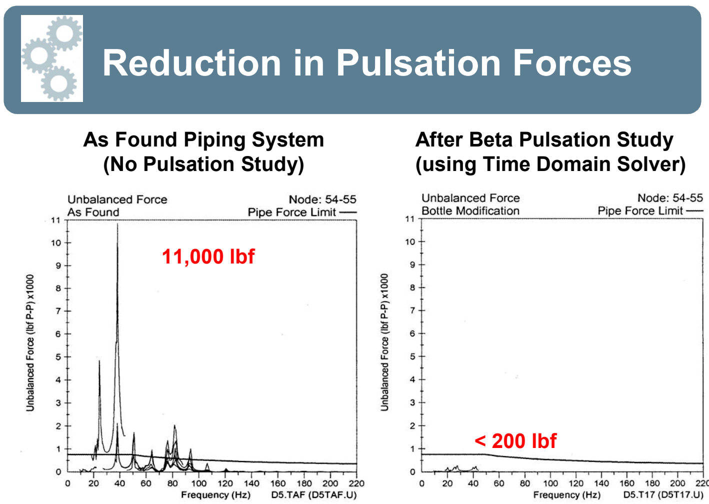


Figure 2.1: Example of Pulsation Forces (before and after a BETA Study)

The pulsation analysis is conducted using a digital model of the compressor's acoustical characteristics. BETA Machinery Analysis (BETA) pioneered the development of digital acoustic simulation software for reciprocating compressor with their proprietary MAPAK software in 1973.

In the late 1990's, the software was expanded to include non-linear Time Domain algorithms, and was rigorously field tested. Non-linear Time Domain simulations are required to obtain accurate predictions of the time varying acoustical characteristics in the system, dynamic pressure drop, and the most effective pulsation control solutions.

> CAUTION: Most commercially available programs are based on the older (and simpler) Frequency Domain approach, which are not able to calculate the Total Pressure Drop in the system, or accurately model higher frequency effects. These programs will not meet the requirements of API 618 (5th edition).

2.2. Scope, Features and Deliverables for Pulsation Analysis (per API 618, 5th edition)

API 618 (5th edition) is the international standard that defines the scope, methodology and guidelines for the pulsation analysis. Depending on the risk of the application, the customer can select the appropriate scope.

- Design Approach 1: empirical Bottle Sizing (does NOT include pulsation analysis).
- Design Approach 2: Pulsation Analysis and Piping Restraint Analysis (mechanical review).
- Design Approach 3: Pulsation Analysis + Piping Restraint Analysis + Mechanical Natural Frequency Analysis (with forced response studies if necessary).

The pulsation analysis is accomplished by modeling the compressor, pulsation bottles, scrubber, piping, heat exchangers, flow meters and other components. The model includes the off-skid piping or yard piping to a suitable termination point such as a large vessel (e.g. an inlet separator or dehydrator) or a main pipe line. An acoustic simulation is performed on the model to determine the pulsations and related forces in the system.

Based on the operating requirements, the analysis will recommend a solution to ensure pulsation forces are below API and BETA guideline. The analysis will consider other factors that influence the design, namely:

- Pressure drop through the system.
- Meter error
- Practicality and cost of the pulsation solution.

<u>Deliverables from the pulsation analysis:</u>

- Recommended orifice sizing, pulsation bottle design, and pulsation control solution
- Summary of predicted pulsations compared to guideline (for the entire system)
- Evaluation of pulsation induced forces compared to guideline (for the entire system)
- Summary of static and total pressure drop results (total pressure drop includes static and dynamic effects)
- Meter error (as required)

2.3. Methodology

2.3.1. Pre-Study For Early Bottle Sizing

A pre-study analysis (or damper check) may be required for some projects. A pre-study analysis is done if the pulsation bottle design must be completed before details of the piping layout, vessel sizes and vessel locations are known. The pre-study analysis includes acoustical analysis of the compressor cylinders and bottles with an infinite length, acoustically non-reflective termination at the lineside nozzle. The design goal for the pre-study is to achieve a pressure pulsation that is 70% or 80% of the lineside pulsation guideline depending on the system configuration.

2.3.2. Pulsation Analysis

An acoustical analysis is conducted for the system when the piping and vessel arrangement has been defined. The design goals for the acoustical analysis include API 618 5th Edition guidelines for pressure pulsations, piping shaking forces, bottle shaking forces, static pressure drop, total pressure drop, and meter error. The approach is to strike a balance between pulsation control and minimizing pressure drop, pulsation bottle size and mechanical design requirements.

The on skid vessel and piping arrangement for skid-mounted compressors is often available when the pulsation bottle design is finalized. The off-skid or yard piping that is not included as part of the compressor package is often not available. BETA has developed a proprietary method to evaluate the sensitivity of the system design to a range of possible off-skid configurations to qualify the design. A complete analysis including the off-skid piping and vessel can be conducted at a later date to evaluate the final design.

The acoustical analysis for the API 618 5th Edition DA2 and DA3 are essentially the same. The main difference between the DA2 and DA3 studies is that the DA3 includes a possible iteration in the acoustical design depending upon the mechanical design. The DA3 study conducted by BETA follows an improved approach in the mechanical system evaluation as noted in section 3.0.

2.3.3. Operating Conditions

API 618 5th Edition states the analysis must include the complete range of operating conditions expected over lifetime of the compressor.

> "Pulsation levels shall be reviewed for all specified alternative gases, operating conditions, and loading steps to assure that pulsation levels will be acceptable under all operating conditions."

If only a few operating conditions are provided to the vibration consultant, then the pulsation analysis will be targeted on this narrow range. However, experience shows that the unit will often be required to operate outside this narrow range because suction or discharge pressure changes, new gas composition, or different flow requirements. When conditions change outside of the narrow range (assessed in the study), then vibration and/or performance problems are more likely to occur.

It is recommended that the entire operating envelope be evaluated during the design stage, to avoid these problems from occurring. BETA will include the full range of pressures, temperatures, cylinder loading and gas compositions in the analysis. This will ensure the unit can run reliably during its entire operating life.

2.3.4. Static and Total Pressure Drop Guideline

The purpose of the pressure drop guideline is to ensure the compressor will be operated efficiently. In API 618 4th edition, the guideline only evaluated static pressure drop. In the 5th edition (released in 2007), the guideline includes total pressure drop – which includes both static and dynamic pressure drop. For more information on these terms refer to BETA's paper published at GMC 2008 (available on BETA's website).

BETA goes a step beyond API 618 requirements by converting pressure drop to power consumption. This provides a more meaningful result for assessing the actual compressor performance, including pressure drop in the piping system.

> CAUTION: most commercial available software packages used for pulsation analysis are not able to calculate Dynamic Pressure Drop. Prior to awarding a pulsation study, we recommend the owner verify the supplier can meet API requirements for Dynamic Pressure Drop.

BETA's report publishes both the Static and the Total (Static + Dynamic) pressure drop. The total pressure drop values are used to evaluate the performance of the final "as built" solution. The chart below is one example in BETA's report that documents the total pressure drop (dP) versus API guideline.

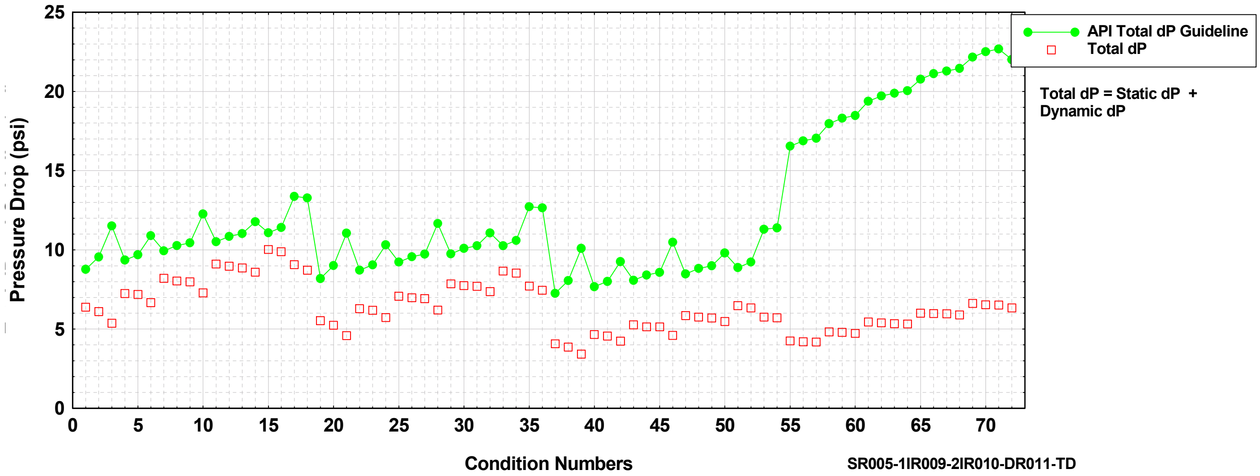


Figure 2.2: Example of Total Pressure Drop Guideline

2.3.5. Liquid Level in Scrubber:

Changes in liquid levels in vessels such as scrubber or separators can effect the pressure pulsations in the compressor system. BETA has developed a proprietary technique to simulate a range of liquid levels in vessels thereby analyzing the compressor system for its full range of expected operation.

2.3.6. Multiple Compressors Connected Together

The additive affects of pressure pulsations from multiple units is included in the analysis. This ensures that the addition of new units to a system does not have a detrimental affect on existing units.

BETA has completed projects with over 20 units at one compressor station (note that there is no limit to the number of units we can include in our software). This capability is required for evaluating different combinations of compressors operating “on line” or “off line”. We can also model different compressor models operating through various speed ranges located on the same header systems. Figure 2.3 shows a facility with multiple units; typical of the projects we regularly work on.

Figure 2.3: Example of a Multi-unit Facility

2.3.7. Flow Measurement Error

Dynamic pressure effects in the piping system will cause measurement error in an orifice meter. The pulsation analysis shall determine the meter error across all operating conditions. Guidelines are established for custody and non-custody transfer meters. For more information on flow measurement error, refer to API 688, or BETA’s published paper (see website).

2.3.8. Results, Solution Alternatives and Cost Considerations

The analysis must balance the competing trade-offs between:

- Capital costs: Increased costs are associated with conservative designs (larger bottles, skid, bracing, etc). A conservative design can add significant cost – e.g., often over $50,000 in labor, materials and overhead.
- Pulsation solution: Should the design reduce pulsations and pulsation induced forces well below the guideline? The mechanical design (pipe support, clamps, braces, etc.) will be less critical if forces are very low.
- Reduced capacity and/or higher operating losses: A simple solution may represent lower capital costs (and an easier solution for the pulsation control designer), but it may add extra pressure drop. An extra 1-5% pressure drop represents a dramatic reduction in throughput, and increased fuel costs. This loss in capacity/efficiency is far more expensive than the incremental capital costs.
- Vibration solution: Should the vibration designer control the forces, or focus on controlling the system response?
- Customer preferences: Does the customer have specific preferences for the package layout?
- Location: Is the package going to be mounted on a concrete block, gravel, or offshore platform?

More or less emphasis on any of these factors can be made based on customer preferences and requirements.

Pulsation Analysis Plots As shown in Figure 2.4, the pulsation report will include plots of pressure pulsations (left) and pulsation forces (right). The consultant should compare the predicted results against the API guideline. These charts will illustrate the amplitude of the forces, as well as the frequency – which is important for the mechanical analysis.

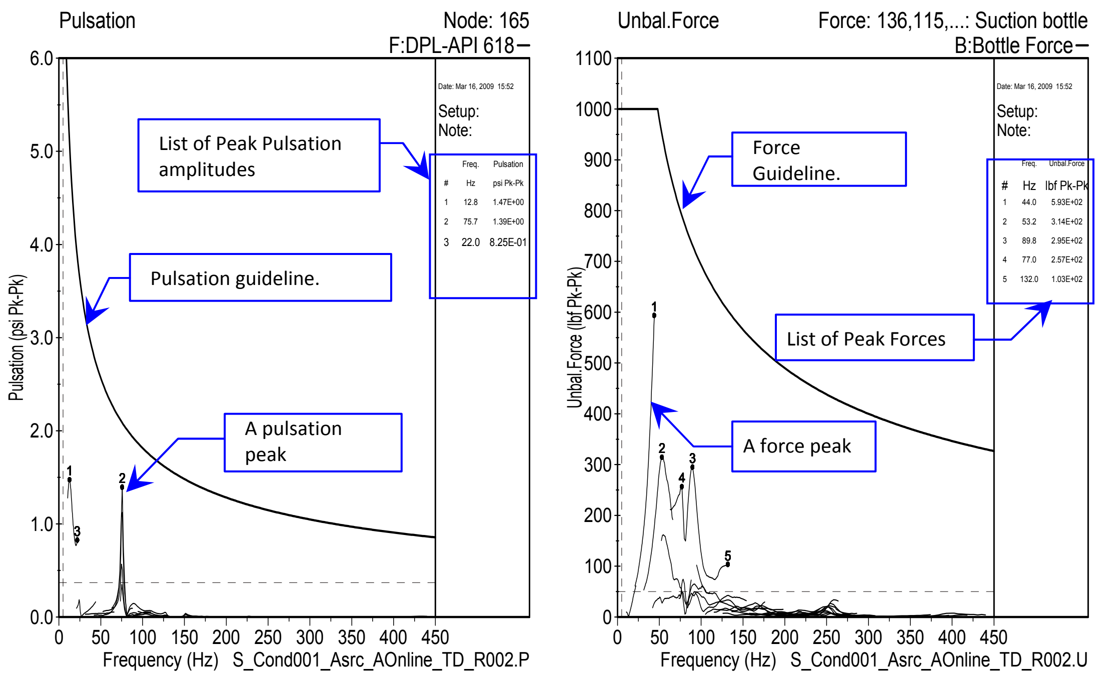


Figure 2.4: Example of Pulsation (Pressure) and Force Plots

Figure 2.5 is just one example of how BETA's DataMiner™ software analysis tool summarizes the results. This unique feature allows the analyst and customer to identify important issues across the entire compressor system. For example, the customer can identify the highest forces for any operating condition (as shown below). DataMiner™ distills data from hundreds of different nodes in the system and at all conditions, frequencies, etc. This effectively replaces hundred of pages of output into one chart – and greatly improves the quality of the solution.

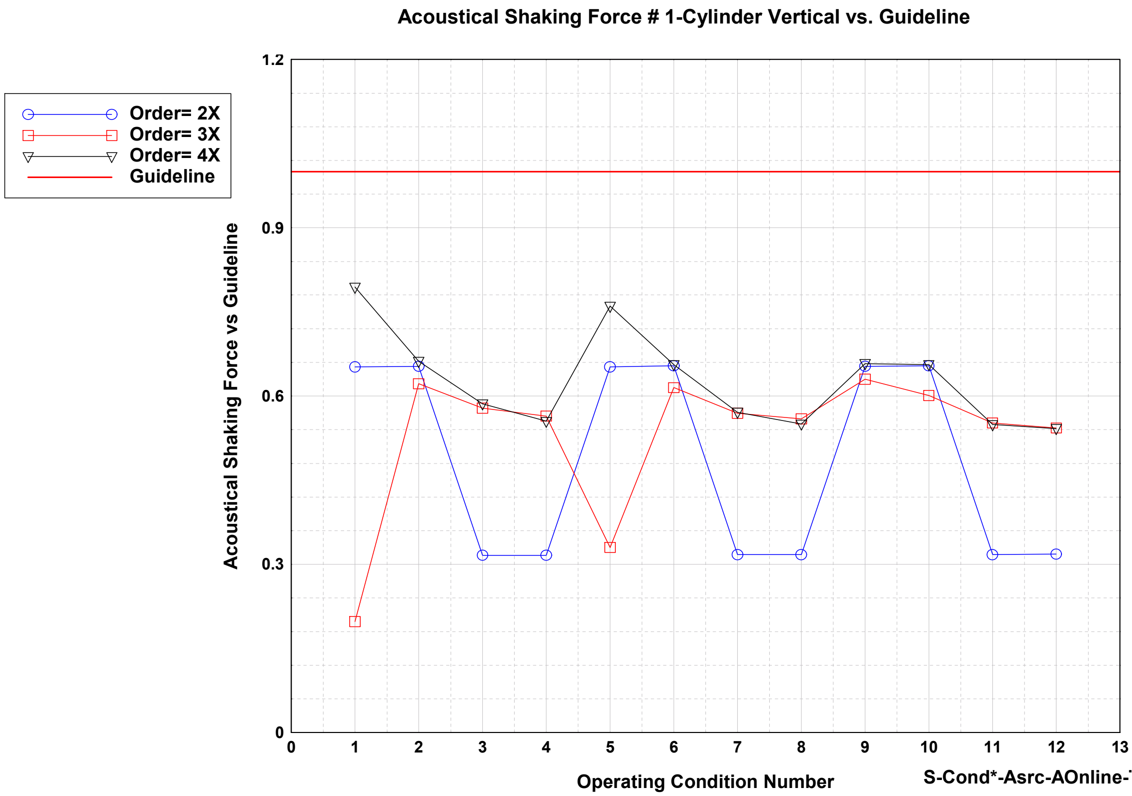


Figure 2.5: Example of BETA DataMiner™ Plot

2.4. Features in a Pulsation Study

API 618 defines the minimum requirements. As shown below, BETA's Design Study offers additional features to ensure improved accuracy, efficiency and value to the owner.

S – Standard feature

O – Option

Features in BETA's Pulsation Analysis	API 618 (5th Ed.)	BETA Machinery Analysis	
Assess Pressure Pulsations & Unbalanced Shaking Forces	✓	**S**	
Recommend Pulsation Solution	✓	**S**	
Meet Static & Dynamic Pressure Drop Guideline	✓	**S**	**Note 1**
Pipe Restraint Analysis (Mechanical Review)	✓	**S**	
Assess meter error (due to pulsation effects)	✓	**S**	**Note 1**
Assess impact of Pressure/Volume Curve due to Pulsation effects		**S**	**Note 1**
Assess all operating conditions	✓	**S**	
Detailed performance report for compressor (at all operating conditions)		**S**	**Note 1**
Time Domain software used to accurately calculate pulsations, dynamic pressure drop and improved bottle design		**S**	**Note 1**
Evaluation of internal bottle forces and stresses (baffles)		**O**	
Rapid bottle sizing program (typically within 48 hours turnaround to meet fabrication schedule)		**S**	**Note 1**
Optimize design service (system performance model to improve performance or reduce capital costs)		**O**	**Note 1**

Note 1: Many vibration suppliers do not meet API 618 5th edition or these other important features because of software or other technical limitations. These deficiencies affect the accuracy of the pulsation predictions, performance results, and other important study requirements. Verify that alternate suppliers offer these features.

We offer two suggestions to ensure an accurate pulsation analysis on your next project:

- Include an up-to-date vibration specification on your next compressor project. A sample specification is available on our web site, www.BetaMachinery.com.
- Screen your pulsation supplier to ensure they have Time Domain software that can accurately calculate dynamic pressure drop. Check to ensure they provide the other features shown above.

2.5. Limitations in Pulsation Studies

- Standard analysis considers pulsation and vibration up to 150 Hz. Internal compressor cylinder gas passage acoustic resonance and shell mode vibration in piping and vessels are outside the scope of this analysis.
- Piping beyond the package limit will be included as long as the required information is available during the start of an analysis. If the information is not available during the course of the on-skid acoustical analysis we will use our proprietary method for performing a sensitivity analysis of the on-skid components to the off-skid components. BETA can revisit its work if off-skid details are made available after study is completed (additional scope).
- The pulsation (acoustical) study does not include a detailed mechanical analysis of the system to avoid resonance/vibration due to other shaking forces (cylinder gas forces, inertia, crosshead loads, etc.) These features are included in a Design Approach 3 (DA3) study.
- Does not assess vibration in the skid and/or foundation design. These are separate analyses.
- Piping stresses are only calculated if the Forced Response study option(s) is selected as part of the DA3 study.

3. Mechanical Vibration Solution

3.1. Reducing Mechanical Vibrations

While pulsation forces can be reduced through the pulsation solution (as outlined in Section 2), the remaining dynamic forces cannot be reduced – they are inherent to reciprocating motion of the compressor. These dynamic forces include cylinder gas forces, crosshead forces, moments and couples, engine related forces, and the remaining pulsation forces.

Per the vibration equation discuss in Section 1, if the dynamic forces can't be reduced then the mechanical design must maximize the stiffness of the piping system (or minimize flexibility) to ensure low vibrations.

At the mechanical natural frequency (MNF) of the system, the flexibility reaches its maximum level (see example MNF in Figure 3.1 below). Per the vibration equation, this is a area where vibration is high. If an excitation force occurs at (or within +/- 10%) of the MNF, the system is called resonant. When resonance occurs, the response can be amplified over 30 times, creating significant vibration problems.

The MNF in Figure 3.1 was measured to be 48 Hz in the suction piping system. This compressor runs at 1000 RPM (16.7 Hz). Excitation forces occur at every multiple of run speed, as illustrated by the red arrows. At 3X run speed, the excitation force is at 50 Hz, and is only 4% away from the MNF, and therefore the system is resonant. To avoid vibration problems, the mechanical design must be modified to separate the MNF 10% away from 50 Hz (3X run speed). For more information on resonance, refer to BETA's Training Tools video on our web site, www.BetaMachinery.com.

3.2. Goal of Mechanical Vibration Studies

A mechanical vibration study is conducted for new compressors, or when modifying an existing unit – especially for larger or critical compressors. This vibration study is included a Design Approach 3 (per API 618).

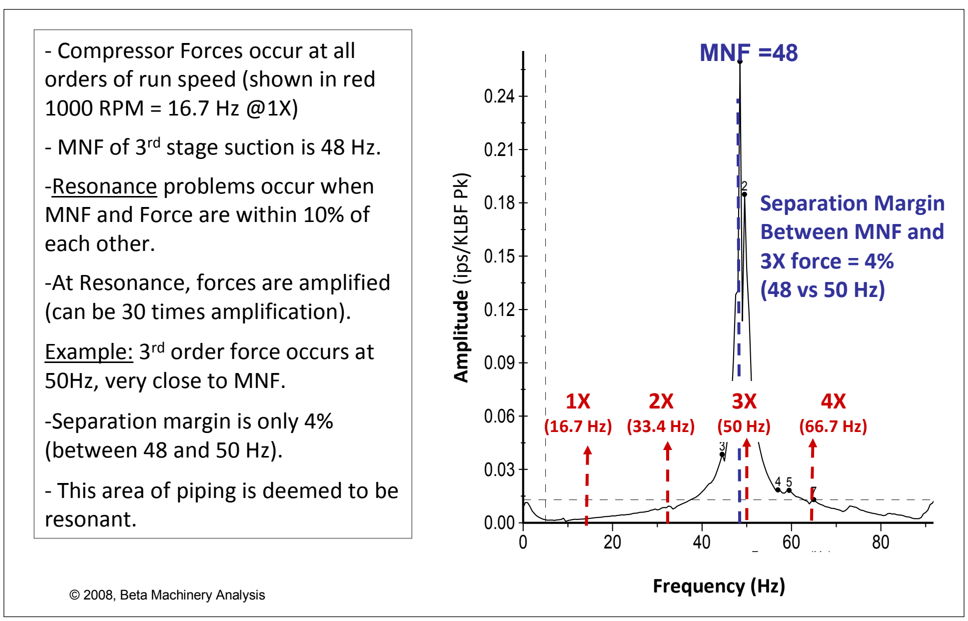


Figure 3.1: Resonance Example of Suction Line (at 3X Run Speed)

The vibration study is based on an accurate Finite Element Analysis (FEA) of the compressor package. The FEA will be used to identify resonant locations (and conditions).

To avoid resonance, BETA will provide recommendations to separate the MNF and excitation force by 20% (+/-). This ensures a safety factor of 10% for fabrication/installation tolerances, plus a 10% frequency band away from the MNF peak. Changing the MNF is accomplished by altering the stiffness or mass of the mechanical structure.

Vibration analysis studies focus on three different areas:

- **Resonance at 1X and 2X run speed:** The highest forces occur at these frequencies, so special attention is place on avoiding resonance in this frequency range. The figure below illustrates typical MNFs for a high speed compressor, and the associated run speed where resonance can occur at 1X and 2X run speed.

Component (example only)	Typical MNF (standard configurations)	Run Speed that Often Causes Resonance (at 1X or 2X orders)
Scrubbers	15 – 30 Hz	> 750 RPM
Cylinders	30 – 50 Hz	> 750 RPM
Bottles	40 – 70 Hz	> 1000 RPM
Piping System	40 – 90 Hz	> 1000 RPM

Figure 3.2: Typical MNFs at 1X and 2X Compressor Speeds

- **Resonance at higher orders:** Above 2X run speed, the amplitude of dynamic forces are generally lower but can still be sufficient to cause high vibration if resonant.

  For high speed units, or when a wide range of speeds are required, it is often impossible to avoid resonance. Vibration will be present. The goal is predict and correct locations in the piping system where vibration amplitudes will be above guideline. A Forced Response Analysis is the accepted approach to calculate the vibration and stress levels in the mechanical system. This technique requires a very accurate FEA that incorporates all significant forces, and field verified stiffness assumptions on compressor frame, nozzles, skid mounting, etc (i.e. boundary conditions).

- **Non-resonant vibration:** Dynamic forces are highest at 1X run speed, and in some cases, can cause the cylinder, bottle nozzle, and associated piping to vibrate even if the system is not resonant.

3.3. Scope and Deliverables (per API 618, 5th edition and other requirements)

3.3.1. Overview

Depending on the API 618 Design Approach, there are different levels of mechanical analysis:

- Design Approach 1 (DA1): does not include mechanical vibration issues
- Design Approach 2 (DA2): includes a piping restraint analysis (see below: 3.3.2)
- Design Approach 3 (DA3): includes mechanical vibration analysis, and if necessary, a forced response analysis to calculate vibration/stress amplitudes (see 3.3.3)

The decision to specify a DA3 is based on a risk assessment of the compressor and its application (refer to BETA's Risk Rating Chart (on our web site, www.BetaMachinery.com).

The API 618 Standard was focused on slow and medium speed machines (and fixed speed applications). These vibration guidelines are now being applied to high speed machines (greater that 750 RPM), and for applications requiring wide speed control. Note that there are some specific limitations that must be considered in the DA3 specifications. This chapter will provide practical recommendations for addressing these limitations.

Guideline for Separation Margin
For the vibration analysis, the key guideline defined by API 618 is the separation margin between the excitation force and MNF:

- At 1x and 2x Run Speeds (2.4 Rule): the goal is to shift the system MNF 20% above the first two orders of run speed (to avoid resonance with the high forces at 1x and 2x). This equates to a minimum MNF of 2.4 times maximum speed.

- For Higher Orders of Run Speeds (up to 150 Hz): The predicted mechanical natural frequencies shall be separated from "significant" excitation forces by at least 20%.

  CAUTION: The confusion in this guideline is the term "significant". API 618 does not explicitly specify which forces should be evaluated and what is considered to be "significant". Based on extensive field research, BETA recommends that the DA3 analysis must include cylinder gas forces and crosshead forces.

3.3.2. Methodology for Design Approach 2: Piping Restraint Analysis

The pipe restraint analysis shall utilize a table of various pipe sizes that indicates the maximum allowable span (based on the maximum compressor operating speed) between piping supports as a function of pipe diameter. The review shall be performed using span and basic vessel mechanical natural frequency calculations to avoid mechanical resonance and the separation margin requirements (see below).

BETA's standard approach goes beyond the API requirements by including the following:

- a system review to ensure the mechanical design follows good design practices
- evaluates items such as the foundation design, skid design, and small diameter branch connections on vessels.

3.3.3. Methodology for Design Approach 3: includes Piping Restraint Analysis and Mechanical Vibration Analysis (with Forced Response Analysis if required)

Along with the DA2 described above, the Design Approach 3 includes a mechanical vibration analysis. Both the pulsation and mechanical methods are coordinated together to find the most effective solution. A flow chart describing these steps is shown in Figure 3.3.

Step 3a: Calculate MNFs
- Predict MNFs (using accurate FEA analysis). Recommend changes to achieve these goals:
  - Avoid resonance at 1X and 2X (goal is to move MNF > 2.4 run speed)
  - 20% separation margin for other orders
  - Pulsation shaking forces < guideline
- Additional Features in Beta's Study to address API 618 deficiencies
  - Assess amplitude and frequency of other dynamic forces (gas forces being the largest). Compare gas forces to acceptable guideline based on field experience.
  - Perform 3D FEA modeling on scrubber bases and nozzles. Other boundary condition assumptions validated through field research (compressor frame stiff, etc.)

If Forces Exceed Guideline; or MNF targets cannot be met

Step 3b: Forced Response Analysis
- Apply dynamic forces including gas forces to FEA model
- Accurately predict stress and vibration amplitudes
- Identify and resolve areas where stress > guideline
- Document vibration and stress amplitude vs guideline
- Options:

  3b.1: Compressor System (frame, bottles, scrubber, and associated piping)

  3b.2: Piping system (off-skid piping, or piping away from compressor)

Figure 3.3: Flowchart for DA3 (API 618, 5th Ed)

The analysis begins with Step 3a to predict MNFs and recommend changes to avoid resonance). If required, Step 3b, a forced response analysis is conducted to assess vibration and stress.

Step 3a: Calculate MNFs

Develop FE Model

The mechanical analysis starts by developing an accurate computer model of the mechanical system (based on FEA). The model will start at the compressor and include the pulsation control devices, scrubber, and main piping, and ending at not less than the second clamp away from the discharge bottle.

A plot of a FEA of one stage of the overall model is shown in Figure 3.4.

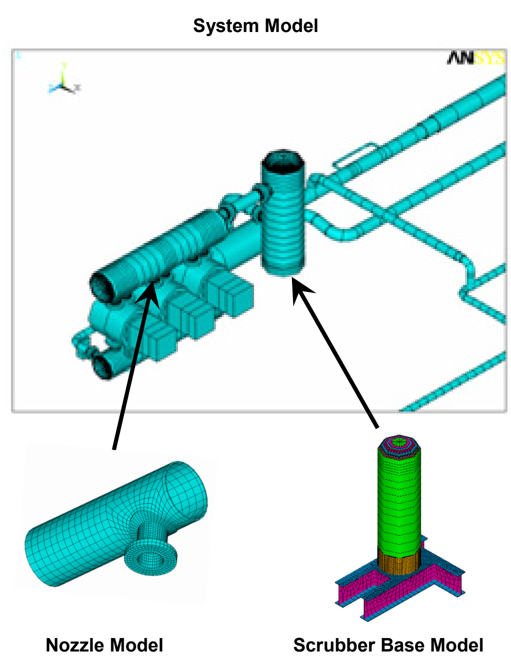


Figure 3.4: Example of FEA Model

Modify Layout to Avoid Resonance

The FE model will identify MNFs for the compressor, vessels and piping near the compressor. The chart below is an example of the MNFs vs. compressor run speed, for a variable speed compressor package.

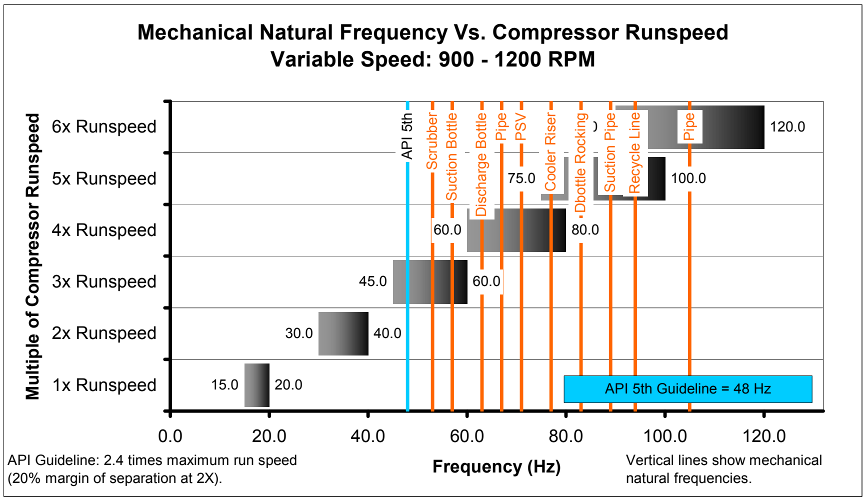


Figure 3.5: MNF vs. Compressor Run Speed
Variable Speed: 900-1200 RPM

Each MNF and mode shape will be assessed to determine if it could become resonant. The goal is to achieve the required separation between MNF and dynamic forces (API 618 guidelines defined in 3.3.1).
- for 1x and 2x compressor run speeds, the goal is to shift the MNFs above 2.4 maximum run speed. This is guideline is especially important for variable speed units. Figure 3.5 illustrates this guideline (see blue line at 48 Hz).
- for 3X, 4X, and higher orders, the goal is to ensure 20% separation.

Figure 3.6 illustrates a MNF that is potentially resonant at the 3X order of run speed. The forces are assessed to determine if resonance will be a problem.

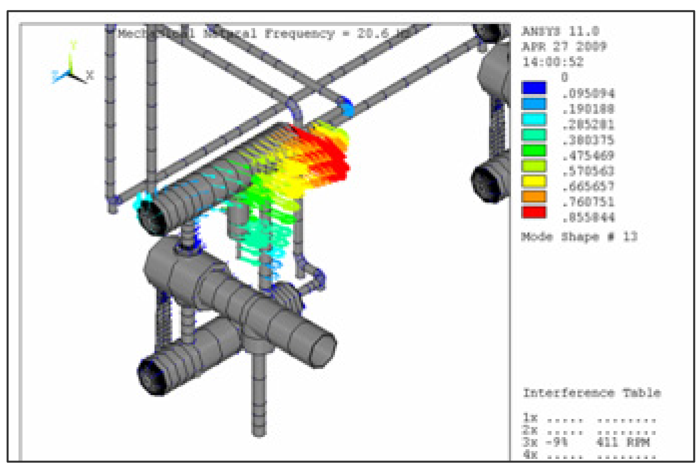


Figure 3.6: Example of 450 RPM Compressor (suction bottles have a MNF of 20.6 Hz. This MNF is -9% below from the 3rd order running speed and potentially resonant)

<u>Required Software for Accurate FE Models</u>

Note that 3D modeling requires accurate modeling of the stiffness of scrubber bases and bottle nozzles. Without these details, the FEA will not have sufficient accuracy and should not be accepted. The example in section 3.3.4 (below) illustrates that error is will be routinely over 15% if poor analytical techniques are employed.

Accuracy starts with a FEA software tools that is capable of modeling 3D solid shell elements, which are necessary to calculate valid boundary condition assumptions. Approved software for this application includes ANSYS, Nastran, or Cosmos. Software programs based on line or beam elements should not be used in this application (including Autopipe, Caesar, etc). Line or beam elements will not accurately model bottle internals, vessel nozzles, scrubber flanges, and other critical details.

CAUTION: Avoid mechanical analysis assumptions based on software utilizing line or beam elements (e.g., AutoPIPE, CAESAR, etc.).

CAUTION: FE modeling techniques must be verified by field measurements. Ask your vibration consultant to verify the accuracy of their modeling approach using field research and measurements.

Potential Resonance Due to Cylinder Gas Forces

Cylinder gas forces must be calculated and reviewed for the range of operating conditions. These forces can become resonant with the pulsation bottles and piping, especially in 3x, 4x, etc run speed range. A practical approach to avoid this resonance is to perform a "limited" forced response of the gas forces acting on the nozzle, bottles, etc. This will determine if the vibration response will become a problem.

This limited forced response is necessary if MNF occurs near 3x, 4x, etc run speed range, and the rod load at this frequency exceeds our guideline.

API 618 has limitations in this area. It does not include a guideline to address cylinder gas forces. Given this confusion, many vibration consultants do not have a method to assess if cylinder gas forces will create a significant resonance problem. As a result, the problem will be addressed using excessive braces, supports or other mechanical means. The cost and need for these severe recommendations may not be needed.

CAUTION: Ensure your vibration consultant has a guideline for cylinder gas forces, and an approach to accurately assess if resonance will be a problem on the cylinder and bottles.

Step 3b: Forced Response Analysis (Vibration/Stress Amplitudes)

This is option is required when the margin of separation guideline or shaking forces guideline cannot be met.

The methodology to calculate vibration and stress involves combining the compressor's dynamic forces with the structural/mechanical design of the compressor package (using the FE model created in step 3a). The forces shall *include cylinder gas forces, crosshead forces, and pulsation forces*. The scope of investigation can vary depending on potential areas of resonance. For example, the analysis may focus on one area of the piping system (i.e., suction bottle), or of the entire piping system.

Forced response analysis can be applied in two locations.

- **Step 3b.1** Compressor area: including compressor cylinders, bottles, scrubbers and piping around compressor. BETA's standard approach for all studies is to ensure the pulsation related shaking forces comply with the API 618 5th Edition design guidelines and/or BETA's own design guidelines. Therefore Step 3b1 analysis is not required for many API 618 5th Edition DA3 studies. Generally this study is recommended for high power applications (>700 HP/cylinder; or 80% rated rod loads).
- **Step 3b.2** Off-skid piping area: including piping away from the compressor (e.g., to off-skid cooler). BETA recommends that the Step 3b2 analysis be done for areas where the shaking force guideline is not met or 2.4x MNF guideline is not met. The Step 3b2 analysis may also be required for exceptional cases where changes in the pressure pulsation control will be difficult, or where the mechanical design is difficult to change.

The output of the analysis will be predicted vibration and stress amplitudes for all points evaluated. The results are compared to guidelines. Note there are different guidelines for cylinder, skid, piping and other regions of the package.

There are two guidelines for the force response analysis: a vibration limit, and an allowable cyclic stress limit. Generally the vibration limit will be the more stringent factor in evaluating the design. However, in many cases the vibration limit may be exceeded if the cyclic stress is acceptable and excitation of other components not included in the piping system model is not a concern.

The chart in Figure 3.7 illustrates the results of the first stage in a compressor system (for the worst case operating condition). Note the locations where the guidelines are exceeded. These areas are investigated in detail (refer to Harmonic Response Analysis plot).

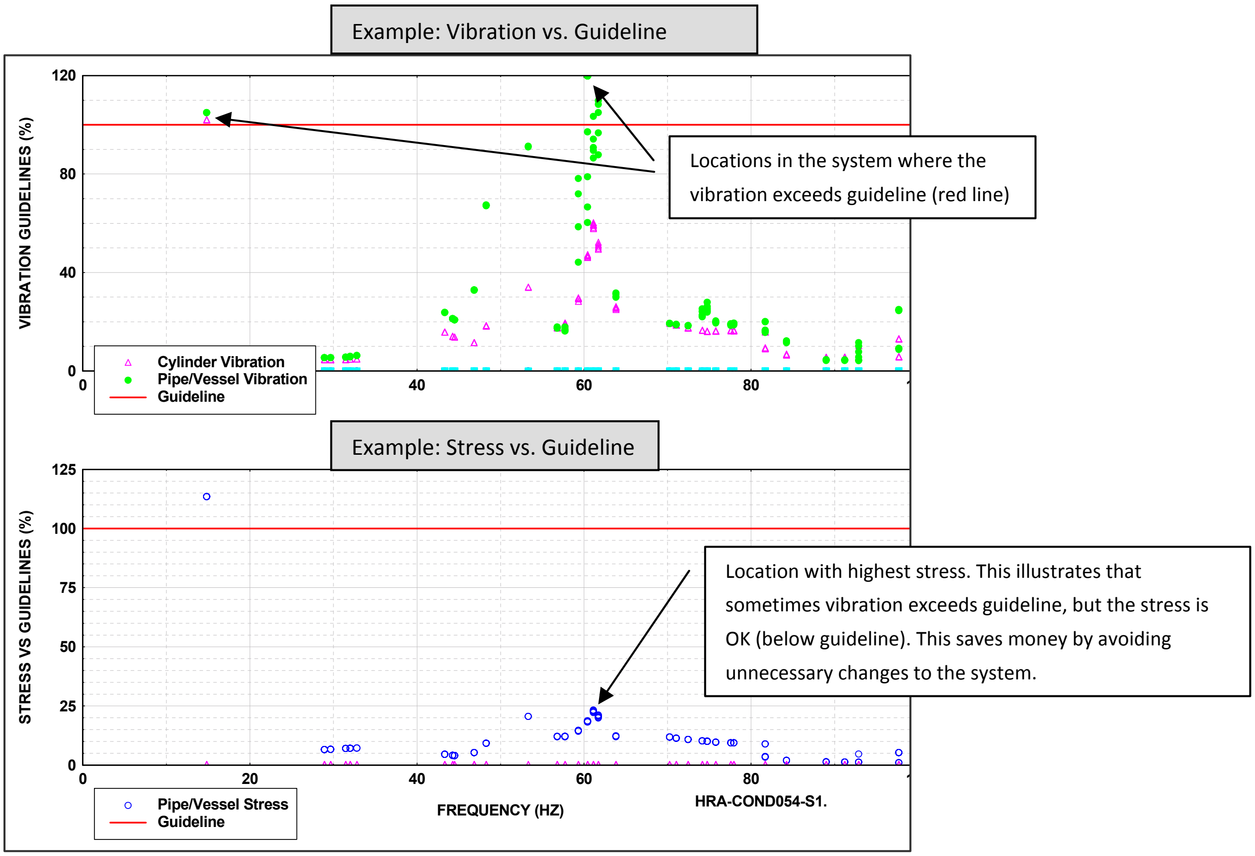


Figure 3.7: Results of Forced Response Analysis

As an added feature (beyond API 618 requirements), BETA will include vibration predictions on the compressor cylinder, crosshead guide and frame. Stress predictions are not included, but are available as an option.

Super-Element Compressor Frame Models

For Critical Applications, BETA can embed a super-element frame model into FE model of the system (see Figure). This provides the most accurate vibration and stress predictions possible – because the frame model accurately models the dynamic stiffness of the frame, cylinders and other components, and improves the boundary condition assumptions for the FE model of the complete package. For more information, refer to Application Note 5 (on our website, www.BetaMachinery.com).

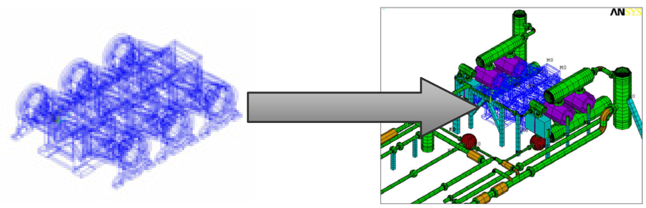


Figure 3.8: Super-element Frame Model (left) is Embedded in the FEA of the Compressor Package (providing superior accuracy for critical compressor applications)

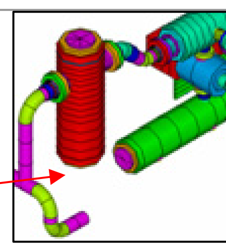
3.4. Required Accuracy in FE Models

API 618 does not define what level of accuracy is required, or the techniques to properly model the mechanical system. As a result, there are inconsistent approaches in the marketplace that can result in poor accuracy.

The example below (Figure 3.9) compares the predicted Mechanical Natural Frequency of a scrubber. One technique popular in the industry is to make assumptions on the scrubber base stiffness (Case 1). This poor accuracy is due to limitations in the FEA software tool, and lack of field verified modeling techniques. BETA does not endorse this approach. Instead every BETA mechanical study includes a full 3-D FEA of the scrubber base to improve the boundary condition assumption (Case 2).

Notice that short cuts in the analysis (Case 1) will result in an unacceptably large error of 16%, compared to BETA's approach which yields results close to the measured values (Case 2). The error may result in a unit that has a mechanical resonance issue, where none was predicted. The less accurate calculated separation may appear to be acceptable, but a more accurate analysis can show otherwise.

MNF Results for Scrubber	MNF	Variance (from actual)	
	Hz	Hz	%
Case 1: FEA does not include 3-D analysis of scrubber base	38.5	5.5	16.7%
Case 2: Accurate 3-D FEA model of base (Beta's standard technique)	33.6	0.6	1.8%
Actual (Measured Data)	**33.0**		



Beta at site conducting R&D on mechanical modeling techniques

Figure 3.9: FEA Models Must Be Accurate

As discussed in section 3.3 (step 3a), an accurate analysis requires the right software tool, modeling technique, and experience. Avoid designs based on simplistic models and boundary condition assumptions.

BETA has dedicated field engineers who calibrate the modeling techniques, and validate the methods. With over 40 years of field experience, we have pioneered many important innovations in this area.

3.5. Retrofit or Modifications to Existing Unit

In cases where the unit is built or under construction before the analysis has started, in-shop and/or on-site tests can be conducted instead of doing detailed mechanical design calculations. The mechanical tests can determine problem areas immediately, evaluate necessary modifications and identify areas that require a detailed mechanical model to determine modifications. This approach is more efficient than doing detailed design calculations on all components.

3.6. Shop Testing

It is common to recommend in-shop and/or on-site mechanical response checks since construction and installation variations can occur. Variations will directly affect the required MNFs and vibration solution. Catching these issues and making adjustments in the shop will be cost effective, compared to the much larger cost of fixing the problem in the field. Modifications may be required, and can include softening or stiffening through bracing, clamping or mass addition for detuning.

3.7. Features in a BETA Mechanical Vibration Study

API 618 defines the minimum requirements. As shown below, a BETA's Design Study offers additional features to ensure improved accuracy, efficiency and value to owner.
S – Standard feature
O – Option

Features in BETA's Mechanical Vibration Analysis	API 618 (5th Ed.)	BETA Machinery Analysis	Other Companies
Calculate and publish MNFs	✓	S	S
Verify accuracy of modeling technique with field research		S	Note 1
Include cylinder gas forces and crosshead forces		S	Note 1
For step 3a, assess cylinder gas forces and potential resonance using a field proven guideline and vibration modeling		S	Note 1
ANSYS or equivalent FEA software		S	Note 1
Accurate vibration and stress prediction (re: Force Response Analysis)	✓	S	Note 1
Publish vibration/stress amplitudes versus guidelines for entire system	✓	S	Note 1
Detailed 3-D FEA of scrubber base and nozzle/shells		S	Note 1
Super element model of compressor frame and full skid model		O	Note 1
Shop test and inspection (at packager's facility)		O	Note 1
Start-up vibration and pulsation check		O	Note 1

Table Note 1: Many vibration suppliers do not meet API 618 5th edition because of software limitations or inaccurate modeling techniques. Other important features may also be missing from the analysis. These deficiencies affect the accuracy of the recommendations, increase the risk of vibration, and will increase the cost of the package. Verify that alternate suppliers offer these features.

3.8. Limitations

3.8.1. Skid and Support Assumptions (Rigid Base):

The mechanical vibration guidelines in API 618 assumes a sound connection between the skid and foundation (or supporting structure). The analysis also assumes that the skid and foundation have been designed/installed to support the dynamical loads.

Based on our field troubleshooting experience, many vibration problems exist because of poor connection details and/or flexibilities in the base. We recommend that the owner or its engineer consider these optional studies as part of the project (contact BETA for information on skid and foundation studies).

3.8.2. Analysis considers pulsation and vibration up to 150 Hz.

Internal cylinder passage acoustic resonances and shell mode vibration in piping and vessels are outside the scope of this analysis. Vibration problems resulting from cylinder motion at frequencies above two times run speed are not covered by our warranty if a cylinder motion analysis (API 618 5th Edition Step 3b1) is not performed.

3.8.3. Inter-tuning on Fixed Speed Machines

BETA's experience has shown that for fixed speed compressors with a rated speed of 900 rpm or greater it is possible to have acceptable vibrations if the mechanical natural frequency of some components is either tuned below the first order or more commonly between the first and second order of compressor speed (called inter-tuning). Allowance must be made for a separation margin of ±20% from the first and second order.

Inter-tuning is strongly discouraged for compressors operating across a wide speed range.

3.9. Specification

To ensure an accurate study meeting the API 618 requirements, BETA recommends that owners or their consultants include a specification on pulsation/vibration studies. Visit our web site, www.BetaMachinery.com for a free specification (either DA2 or DA3 study).

4. Compressor Station Performance Analysis

4.1. The Problem

There are many documented cases where overall performance of a reciprocating compressor system (i.e., compressor plus bottles, coolers, and all package and plant piping) falls short of performance. This has become a more frequent issue when high speed compressors are employed on low ratio, high flow applications; however, significant problems have also occurred on other upstream and midstream reciprocating compressor applications.

Even when compressor OEMs and system designers meet their contractual obligations, owners may encounter performance shortfalls;

- from higher than predicted system pressure drops through vessels, piping, etc.,
- from miscalculation of pressure drops through coolers,
- from the effects of pulsations at the compressor suction and discharge valves, or
- from operating outside the design points that were considered during the initial pulsation study.

Conventional industry practice is for a packager to build a reciprocating compressor system using the compressor OEM components. The compressor OEM, then, guarantees performance up to the compressor flanges, which is all that the OEM has control over. The packager or systems integrator relies on the compressor OEM's data, and then provides a generic assumption of pressure drop through the rest of the package. Because of these assumptions, the supplier cannot provide a meaningful guarantee of overall system performance. The problem won't appear until the unit is installed and in production. Only then can the owner test the unit and identify if a performance shortfall occurs. Sub-optimal performance represents a significant financial loss.

It is desirable for owners and system designers to have the ability to quickly and economically compare different designs for optimization. Owners would like to be able to reliably verify that a selected compressor system will meet their requirements over the full range of potential applications and need. They would also like a way to predict accurate benchmarks that they are able to measure in the field and to track operating conditions at specific test points. Finally, operators would like to have more comprehensive information for operating their compressors to ensure that unsafe, unreliable and/or inefficient areas of operation are identified before attempts are made to operate in regions of potential compromise.

4.2. The Solution: System Performance Analysis and Design Optimization

To address these industry challenges, **Beta Machinery Analysis** and **ACI Services** jointly developed an analysis called *System Performance Model (SPM)*™ . As shown in Figure 4.1, the SPM evaluates the complete reciprocating compressor system including cooler, pulsation vessels, separators and all piping. This advanced compressor performance modeling program is integrated with the total pressure drop data (from the pulsation study) and other design criteria.

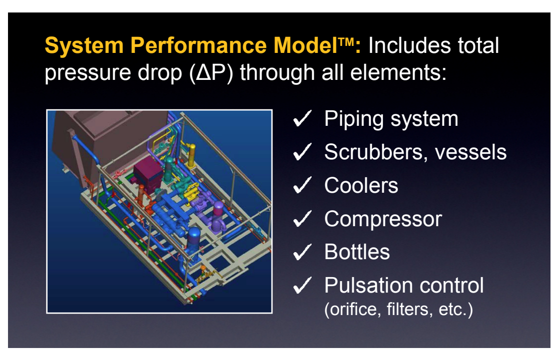


Figure 4.1: System Performance Model (SPM) for Reciprocating Compressor Design

This service can include any or all of the following five different options when evaluating the compressor station's system performance:

4.2.1. Validate Capacity/Performance For New or Modified Compressors

During a project, the packager utilizes the compressor's OEM performance program to size the unit over the various conditions. As already discussed , generic assumptions are made regarding pressure drop, pulsation effects on the performance, losses through the cooler, etc. This assured pressure drop can result in as much as +/- 15% error in performance predictions. Many customers find out that the unit will not meet the required specification once the system piping is considered. Note that customers want to avoid both positive and negative variances.

Figure 4.2 is an example that illustrates the variance between actual performance (SPM) vs. the assumed performance (based on OEM program and generic pressure drop assumptions). This is a 6 throw, 4000 HP compressor. In this project, the variance was -2% to +4.5%. At condition 3, the production is off -2%, resulting in $7 million reduction in throughput (per year).

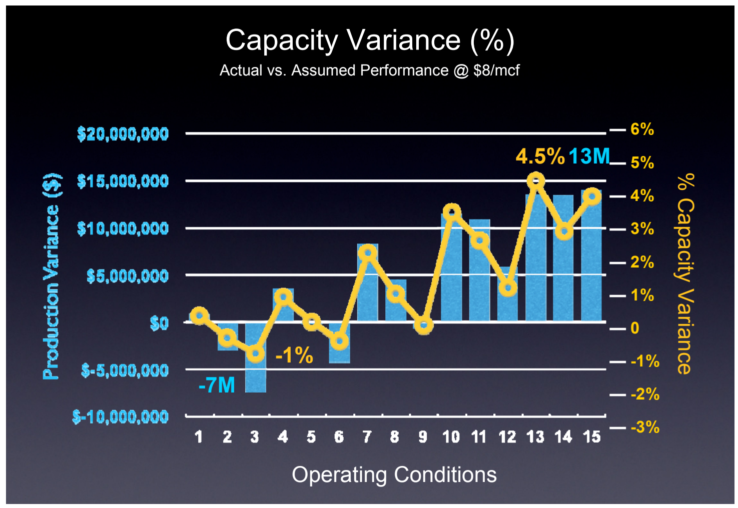


Figure 4.2: Identify Capacity Variance (Actual "System" vs. Initial Assumptions) Using SPM Analysis Software

The SPM™ software evaluates the entire system, including all the dynamic losses and at all operating conditions. This identifies the variance between the assumed performance and the actual system performance. If the performance does not meet the required specification, changes can be made prior to finalizing the design.

4.2.2. Optimize the Compressor Design

API 618 recommends that owners consider life cycle costs and improved efficiency in the compressor design.

The SPM™ analysis can be used to evaluate different designs and optimize the solution. The optimal design balances economics, performance, vibration and other key variables. Improving the throughput, by even a small amount, can have a significant financial benefit to the owner.

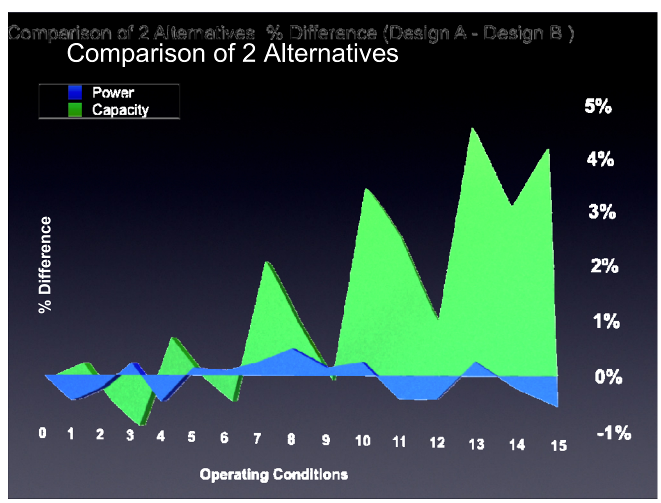


Figure 4.3: Compressor Design Optimization Using SPM Tool

In this example (Figure 4.3), BETA compares two compressor designs. The goal is to identify which option has the optimized performance and generates additional financial returns. The chart illustrates the difference between the two alternative designs and illustrates the incremental capacity (in %) for the key operating conditions. The owner can then assess the economics based on the improved throughput. In this case the data is confidential, but we can say the incremental revenue is many $ million/year.

4.2.3. Model The Entire Operating Envelope

For pipeline applications it is critical to model a wide variety of conditions, including future design scenarios. In the past this was often difficult and very time consuming.

With BETA's new SPM™ and Dataminer™ programs, it is now much faster and more cost effective to model the complete operating envelope (which typically means over 100 different operating conditions). Evaluating the entire operating envelope will greatly improve the overall reliability of the package.

4.2.4. Evaluate Multiple Compressors at a Station

BETA can analyze multiple compressors and evaluate the interaction of the different units. We have completed projects with over 20 units at one compressor station (note that there is no limit to the number of units we can include in the model). This capability is required for evaluating different combinations of compressors operating "on line" or "off line". Figure 1.4 shows a facility with multiple units; typical of the projects we regularly work on.

Figure 4.4: Beta's Software Effectively Models Multi-unit Compressor Stations

4.2.5. Integrate System Performance Data in the Control Software

The compressor's performance characteristics can be imported into the PLC or compressor control system (for the entire operating envelope). This enables operators to run the units more efficiently and generate higher throughput.

BETA makes the process easy, as we are able to create our performance model from a variety of sources. Typically, the packager provides performance runs for our modeling purposes. For older units that are being modified, the original performance runs may not be available. In these cases we can usually obtain the required information from HP curves, etc., or by contacting the OEM on behalf of the client.

The SPM™ and Dataminer™ analytical tools are unique to BETA, and provide better decision making information for customers operators.

5. Summary

5.1. Vibration Control – Must be Specified

To avoid vibration and reliability problems, include a specification for pulsation/vibration study with the compressor package bid documents. For a generic specification on Design Approach 2 or Design Approach 3, visit www.BetaMachinery.com.

5.2. Scope of Vibration Analysis

The following elements can be included in a vibration study. Contact Beta, info@BetaMachinery.com, for advice on what elements are recommended for your specific application.

Location	Study	Options	When Required
Compressor and Package	Pulsation and Mechanical Analysis	Design Approach 2 (DA2): pulsation analysis and basic mechanical review. Design Approach 3 (DA3): pulsation analysis and detailed mechanical analysis to identify and resolve mechanical vibration. In some situations, a Forced Response Study is required to calculate vibration and stress amplitudes.	Large units (typically over 500 HP) and important applications (refer to risk rating chart on BETA's website).
	Torsional Vibration Analysis	Assess torsional system (crankshaft) to avoid vibration and failures. Sizing recommendations for couplings, flywheel, and other components. Optional: Forced Response Analysis to assess stress amplitudes	Required for new design, or if new load step, operating condition, etc.
	Compressor Design Optimization	Evaluate proposed compressor system to improve capacity, efficiency, and reliability (and reduce pressure drop and fuel gas). System Performance Model used to assess total pressure drop across the piping system, and at all conditions.	Pipeline, midstream, injection withdrawal applications. Other compressors when customers want to reduced losses.
Piping	Piping Flexibility (Thermal) Analysis	Predict cooler nozzle loads and piping stresses from thermal cycles, static pressures, weights, and bolt-up strain.	When coolers are located off the skid.
Skid	Dynamic Vibration Analysis	Evaluate skid design to avoid vibration and resonance problems.	To optimize the skid design and avoid resonance.
	Lifting, Loading	Evaluate stresses due to lifting, loading, transportation, etc.	For new skid.
Foundation/ Offshore (Platform or FPSO)	Dynamic Vibration Analysis	For foundations or structure, provide recommendations to avoid resonance and vibration problems. Ensure study includes stress and vibration predictions.	For any offshore application or large land based foundation.
On site Start Up	Baseline Vibration Check	Baseline should be performed soon after start-up. Check vibrations on frame, driver, piping, skid, and base. Spectral data, waterfall, speed sweeps and ODS analysis are methods used to identify problems. Option: Compressor Performance Analysis also available.	Good practice, especially for large or critical applications, and for remote locations.

If you have any additional questions, please contact the helpful staff at Beta Machinery Analysis, or see the resources available on our web site, www.BetaMachinery.com.

BETA

MACHINERY ANALYSIS

Keeping it running smoothly

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