Implications of the New API 618 (5th Edition) for Packagers, OEMs and End Users

Background

Application Note1 has two parts: 1a* outlines the requirements of API 618 5th Edition ("the Standard"). This Application Note, 1b, shows how the Standard affects packagers and end users. Each point is numbered and outlined in more detail in this Application Note:

1. Ensuring Mechanical Natural Frequencies (MNFs) meet API 618 guidelines present design challenges, especially for higher speed units and variable speed units.
2. The Standard does not define, nor specify, guidelines for cylinder stretch forces. These forces can be a significant issue for the mechanical design. Beta Machinery Analysis (Beta) provides a recommended approach for these loads.
3. API 618 is a minimum requirement. There are many ways to **reduce the total cost and improve efficiency of compressor packages**, however, these optimization efforts must be specified by end users, or packagers.
4. There are **commercial issues when quoting Design Approach 3 (DA 3) Studies**. Customers and packagers need to be aware of the confusion and potential impact to their budgets when issuing RFQs for forced response studies
5. The Standard does not specify how consultants should perform pulsation and mechanical modeling studies to obtain accurate results. Approaches that produce poor or inconsistent results should be avoided.

1. Ensuring MNFs Meet API 618 (5th Edition)

The 5th Edition includes two specifications relating to MNFs:

a) The mechanical natural frequencies of bottles, piping, and cylinders must be above 2.4x compressor speed as shown in the figure on the right (Minimum MNF Guideline).

b) A separation margin of ±20% is required between the calculated mechanical natural frequencies and *significant excitation frequencies* (Separation Margin Guideline).

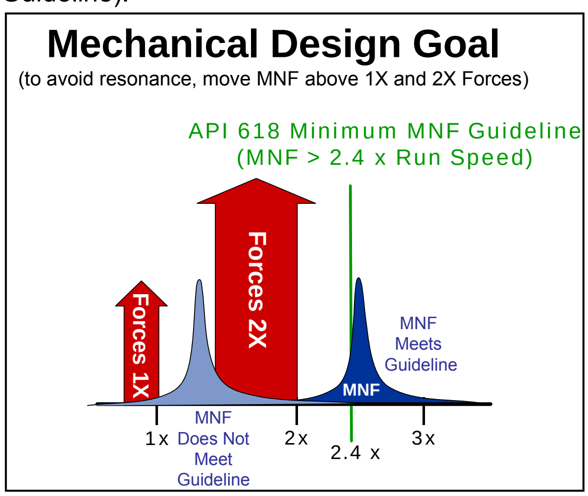
1.a. Minimum MNF Guideline

The Minimum MNF Guideline represents a significant design requirement for high speed compressors (1200 to 1800 RPM). In general, the piping or vessels must be much stiffer than slower speed units. Early communication between the compressor packager and designer of the pulsation and vibration control is necessary to ensure acceptable vessel and skid designs.

The chart below illustrates the Minimum MNF Guideline (for different run speeds)

Minimum MNF for Compressor System (based on different run speeds)

Maximum Run Speed (RPM)	(Hz)	Minimum MNF Guideline:
900	15	36 Hz
1200	20	48 Hz
1800	30	72 Hz



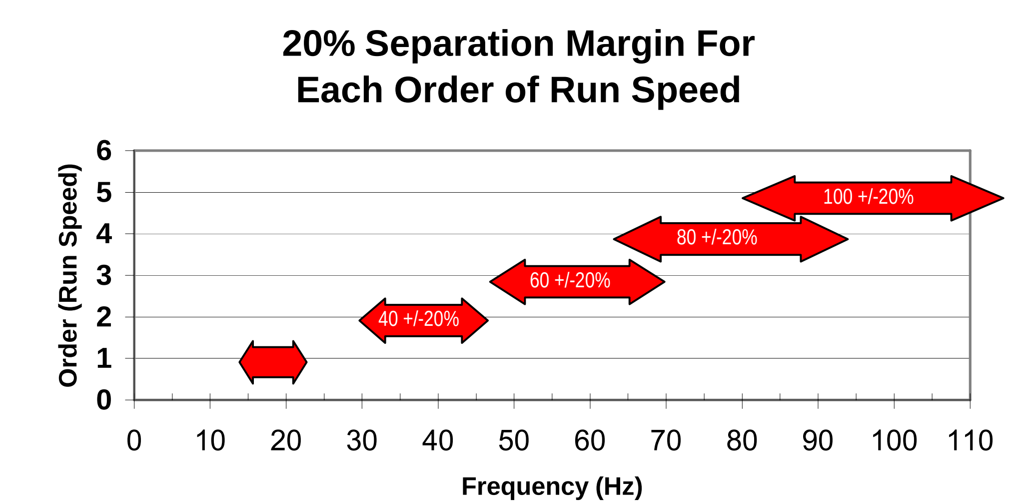
For slow and medium speed units, the Minimum MNF Guideline is not a difficult design problem. For high speed machines, however, the design becomes much more challenging. Here is why:

Compressor Component (example only)	**Typical MNF** (standard configurations)	**Run Speed That May Violate API Sep. Guideline**	**Cost/Design Implications if MNFs Must be Moved Higher**
Scrubbers	15 – 30 Hz	> 375 – 750 RPM	Extra costs to add braces or change scrubber design
Cylinders	30 – 50 Hz	> 750 – 1250 RPM	Potential need for outboard supports
Bottles	40 – 70 Hz	> 1000 – 1750 RPM	Bottle supports likely necessary
Piping System	40 – 90 Hz	> 1000 – 2250 RPM	Pipe braces or pipe layout changes will be necessary

1.b. Separation Margin Guideline

The requirement for a ±20% separation margin from the MNF and *significant excitation frequencies* is problematic in the Standard. The definition of *significant excitation*, that is, a force amplitude, is not given in the Standard. Also, the *frequencies* to be considered are not defined in the Standard.

One interpretation of the ±20% separation margin is that it applies to all frequencies above 2.4x compressor speed. However achieving a separation margin of ±20% is not possible at higher orders. For example, a compressor operating at 1200 RPM (20 Hz) will have dynamic forces at 20 Hz, 40Hz, 60 Hz, 80 Hz, etc. As shown in the following chart, applying a ±20% margin on each of these frequencies results in an overlap for all orders of compressor speed greater than the second order. Therefore, this separation margin criterion is not practical even for a fixed speed compressor.



API 618 Guideline requires excitation forces to be separated from an MNF by over 20% (separation margin). An excitation force will occur at every order of run speed. The graph above illustrates the separation margin will overlap above the 2nd order. This means there is no room to place the MNFs for the compressor system.

Packager and OEM tips for improved design include:

- Fabrication practices such as installation and mounting details – very important (to the skid).
- Vessel design (length vs. diameter) vs. mounting design – can dramatically affect MNFs.
- Accurate Finite Element Analysis (FEA) modeling that closely matches the real MNFs – short cuts in modeling create high risk – see Section 5, on page 5.

In some cases, it may be impractical to reach these high frequencies. Inter-tuning can be an option if approved by the end user and packager (refer to our Application Note #3* for more details).

End user considerations:

- Early involvement with the packager and vibration consultant (Beta) is recommended to discuss mechanical design options (early in the project avoids costly changes later)
- Determine how much risk you are willing to take on. Complete a risk assessment to determine the level of analysis that is required. Beta has a risk assessment matrix that can assist with this step. Your specification to the packager, or OEM must specify the analysis steps necessary to minimize your risk (for example, a Forced Mechanical Response Analysis of the Compressor Mechanical Model (Step 3b1) must be conducted).
- Specify correct modeling procedures for more accurate results. This includes assumptions on boundary conditions, compressor frame stiffness assumptions, etc. (see Section 4, page 4).

Other references on mechanical design include Beta's Application Notes numbers 3, 4, 5, and 6*.

2. Cylinder Stretch Forces Must Be Addressed in The Design

Beta, and other leading consultants, have long recognized that the forces acting on the inside of the compressor cylinder are a significant source of excitation at all orders of compressor run speed. These forces cause the compressor cylinder to move away from, and towards, the compressor frame. This motion is commonly called frame stretch, or cylinder stretch. Cylinder stretch motion can cause high frequency vibrations on the bottles and piping close to the compressor. (Reference article: *Cylinder Stretch as a Source of Vibration in Reciprocating Compressors*, 1991*).

These forces are not described, nor guidelines specified, in the 5th Edition of the API 618 Standard. Beta has developed guidelines for assessing these forces to determine the potential for causing vibration problems in the design stage. We have also developed design criteria for assessing fundamental vibration modes for pulsation bottles at high orders of compressor speed. These Beta design guidelines are applied on all mechanical studies in the API 618 4th Edition M5 study, or API 618 5th Edition Design Approach 3 (step 5 of section 7.9.4.5.2).

We have also developed a risk assessment procedure that can be used in the quoting stage to determine the potential for cylinder stretch related vibration problems. Factors such as power per cylinder, rod load, speed range, and others, are strong indicators that additional analysis is warranted. This additional analysis was included as the 4th Edition M6 study. The 5th Edition describes this as a Step 3b1, Forced Response Analysis of the Compressor Mechanical Model (section 7.9.4.2.4.3).

Packagers/End Users Considerations:
Beta recommends that the end user and/or packager complete the risk assessment for the package to determine if the Step 3b1 analysis is required. The requirement for this study should then be included in the request for quotation to suppliers of the pulsation and vibration control design.

The mechanical design guideline to avoid resonance is now an important design specification in the new Standard that brings a higher level of analysis to the pulsation and vibration control design. Variable speed drive units further complicate the design.

3. An Optimized Compressor Design is an Option to Reduce Total Life Costs

API 618 5th Edition only specifies the minimum requirements. However, the new Standard recommends innovative approaches *"should be aggressively pursued by the manufacturer [packager] and user"* during the design and operation to reduce the total life costs and energy conservation.

Here are examples that illustrate the significant savings available through Design Optimization:

- ***Optimized pulsation solution reduces horsepower losses***. Unless specified, the packager and consultant will deliver a solution that meets pulsation and vibration guidelines and may not optimize pressure drop. A more efficient design is often possible with relatively small engineering effort. Refer to Beta's Case Study O1* for an example where there are two types of savings:
  - Reduced horsepower results in fuel gas savings greater than $75,000 every year. The savings generated a 6 month payout.
  - If additional gas can be shipped, the additional horsepower can be used to compress more gas. The incremental gas production is over $3 million per year.
- ***Optimized pulsation solution reduces cost of bottles***. During a recent project, a pulsation solution recommended a 26" OD bottle for 1 stage of a 6 throw, 3 stage compressor. This bottle design was the conservative solution that met the API specification. Using our optimization techniques, Beta was able to recommend a 16" OD bottle without an increase in the pressure drop or changes to the support design. This bottle generated the following savings for the packager:
  - $20,000 reduction in bottle costs
  - $20,000 reduction in skid costs (small bottles had a significant impact to the skid design)
  - Approximately $20,000 reduction in factory overhead (reduction in time to build the unit, allowing for other projects to be started).
  - Net impact = $60,000 savings – significantly more than the cost of the study!

There are many other examples where optimization generates reduced total costs.

Implication to Packagers and End Users:

1. An optimized design will not happen unless specified, because the packager and end user generally choose a consultant based on the quoted cost (minimal effort).
2. Software tools are now available to enable rapid optimization. Beta's DataMiner™ is an example of one of the tools that allows the consultant to quickly and efficiently find the best solution. The incremental cost is minor, while the upside value is significant.
3. Optimization works best when the end user, packager, and pulsation consultant meet to compare options and agree on the final design.

4. Commercial Issues (When Quoting DA 3 Studies)

End users and packagers have to adjust their quoting process to avoid confusion with DA3 studies. This new Standard has commercial and project management implications.

As discussed in Application Note #1a, the Design Approach 3 in the new Standard includes several steps where a forced response analysis may be required if the results of the pulsation analysis and the mechanical analysis (MNF modeling) do not meet guidelines. This creates the following issues in the quotation phase:

- Uncertainty if the forced response analysis will be required and what the associated cost will be of these contingencies.
- The scope of the forced response study may not be apparent during the quotation phase. Depending on the situation, the scope of the study, or studies, could be small, or quite large.

The consultant responsible for the pulsation and vibration control design faces these commercial issues, which ultimately affect the quality of the study:

- should the consultant bid a low price for this study (in order to get the project), and assume the forced response studies can be avoided; or
- bid a realistic price for the studies, even though the consultant realizes they may not be required (and jeopardize losing the job).

The following ideas will help avoid confusion and ensure consistent quotations.

Implication to Packagers and End Users:

- Beta has conducted design studies and field studies on thousands of reciprocating compressor packages. We have an understanding of the units' general characteristics and when the forced response will be needed. Contact our application support for advice, or complete our risk rating chart.
- A Forced Response Analysis of the Compressor Mechanical Model (Design Approach 3, Step 3b1) is typically required when:
  - HP/cylinder >750, or rod loads exceed 80% rated rod load,
  - Wide speed range operation is required (more than 25% of rated),
  - Compression ratio is below 1.7, or
  - There are critical applications (remote location, high availability required).
- Forced Response Analysis of the Piping System (Design Approach 3, Step 3b2):
  - The analysis is seldom required for standard compressor packages. The pulsation design will typically reduce pulsation forces to low levels. The mechanical analysis will avoid resonance at the first and second order of compressor speed where the highest pulsation energy typically occurs. These two factors generally result in low piping vibration.
  - The analysis may be used if:
    1. Optimization of the system design is specified. For example:
       - Determining optimum bottle sizes for multi-unit projects where trade-offs must be made in the design of the piping support and long-term operating costs, or reduced production, from high pressure drop.
       - Trade-offs in the pipe support and pipe layout design around coolers are required to meet the MNF guidelines and thermal expansion (nozzle load) guidelines.
    2. The project involves an existing facility, where making changes to meet the new Standard guidelines is costly (construction costs, lost production).
- Compare "apples to apples" from suppliers of the pulsation and vibration control design. Here are a couple of approaches:
  - Provide a firm quote on DA3 – step 3a. Compare suppliers based on this price. [Ask for optional price for forced response studies, realizing that they won't likely be needed.]
  - Quote full DA3 (including both forced response studies) – assuming full analysis is required. Expect full analysis from the consultants (including stress and vibration plots). Require all consultants to quote a full study and pre-qualify vendors to ensure they can provide stress and vibration plots.

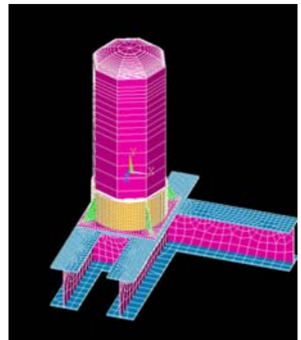
5. Factors Affecting Accuracy of Vibration Analysis

API does not specify how to perform simulations and modeling. Different levels of quality exist in the industry (buyer beware). The following are 4 key areas to specify, to ensure adequate quality.

1. **Pulsation Analysis**: It has been documented in numerous technical articles that Time Domain (TD) algorithms provide superior accuracy over the older Frequency Domain (FD) algorithms. Recommendation: Specify that pulsations be modeled using TD and FD algorithms. TD output should be included in the report; it should include dynamic pressure drop and plots of forces that exceed guideline (for all conditions and all frequencies under 150 Hz).

2. **Scrubber MNF calculations**: (DA3 studies, step 3a): FEA models are used to determine the MNFs for each component in the system. For scrubbers, the most important factor is the boundary condition assumptions (between the scrubber and the skid). The figure, previous page, illustrates the details needed for accurate analysis (mounting plate, bolts, beams, and local skid construction).

Simplistic FEA models will assume a rigid scrubber base or generic estimate of stiffness. Beware of models with "rigid support," or "anchor," or "assumed stiffness." *These have proven to be inaccurate and should be avoided.* Case studies are available illustrating that over 15% error is associated with simplistic models. High error can mean resonance, or excessive costs (conservative mechanical design).

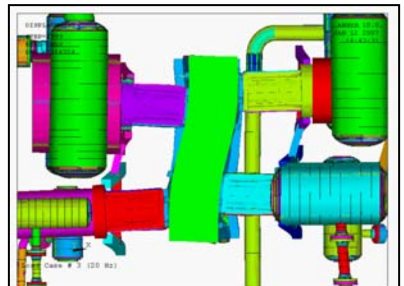


FEA model (scrubber) must include base details as shown: mounting plate, bolts, beams, and local skid construction.

Recommendation: Specify that the scrubber FEA model must include mounting details including beams, mounting plates, and localized skid design; and that the report is to include a copy of the FEA models employed.

3. **Compressor Stiffness Assumptions**: (DA 3 Studies, steps 3a, 3b1) Due to high gas forces, the compressor frame cannot be considered a rigid body for dynamic studies, even when mounted on concrete. Accurate stiffness assumptions are required when modeling the compressor MNFs (step 3a) and force response analysis of the compressor and bottles (step 3b1).

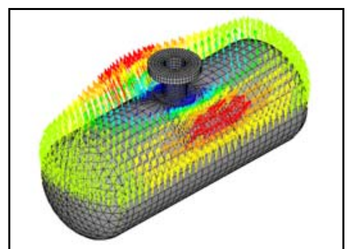
   Recommendation:
   - For critical applications requiring the highest accuracy, specify the mechanical model includes the compressor frame. Super element models of frames have been developed that result in highly accurate models without affecting the analysis time compared to alternative methods.
   - For all other studies, specify that the compressor frame is not to be assumed a rigid structure. The consultant to determine the appropriate compressor stiffness assumption based on field proven results and review of the compressor skid and foundation design.



Don't assume frames are rigid. This FEA model of a compressor frame illustrates (exaggerated) local flexibility.

4. **Pulsation Bottle Nozzle Flexibility**: (DA3 Studies, steps 3a, 3b1) Pulsation bottle MNF depends on nozzle connection flexibility. All mechanical models must employ 3D FEA techniques to calculate shell flexibility accurately. Simplifying assumptions are not valid.

   Recommendation: specify that all mechanical models must employ 3D FEA analysis to calculate shell flexibility.



Nozzle – Shell flexibility must be accurately calculated for mechanical models using 3D FEA techniques

Summary

These specifications will ensure accurate vibration analysis, improved reliability (for end users), less warranty costs (packagers), and a level playing field when quoting on projects (for vibration consultants).

*All Application Notes, Articles, Case Studies, and support tools (risk rating chart) mentioned in this Application Note are available, free of charge, on our web site, www.BetaMachinery.com.

Please contact Beta for supporting references on these technical issues.