GE Oil & Gas

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Compressor general arrangement dynamic design guided by preliminary cylinder manifold forced response

Abstract

Machinery today must have ever-increasing performance capabilities, which also means greater compression system vibration risks. A thorough knowledge of dampener pulsation force phenomena and related best practices is essential to significantly reducing system vibrations. While loads acting on the foundation are defined early in the process to allow for proper design, "cylinder gas loads" depend on compressor data sheet specifications and cannot be adjusted without changing requirements. Due to their high amplitudes and frequency spectrums, some exciting frequencies are more likely to coincide with the natural frequencies of the mechanical system, which can generate mechanical resonance phenomena.

For these reasons, extensive efforts are required during preliminary cylinder manifold response studies to guide compressor general arrangement (GA) design. A cost-effective solution provides model creation through the use of specific software that includes compressor standard elements selection for dampener building. In addition to significant cost benefits, this software helps the designer simulate multiple configurations by quickly rebuilding the model to explore several solutions for enhanced system vibration control.

A finite element method (FEM) specialist is not required for the model buildup, as the software allows the designer to apply cylinder gas loads automatically and run the analysis. The software then compares the results to allowable values. If the allowable limits are exceeded or if design changes are needed, the GA designer can change the input values easily and iterate the loop until satisfactory results are achieved. These software iterations can be performed quickly to produce quality results for dampener and support designs with reduced vibration risk.

Nomenclature

FEM	Finite Element Method
RPM	Revolutions Per Minute
CAD	Computer Aided Design
MNF	Mechanical Natural Frequency
CMS	Cylinder Manifold System
GA	General Arrangement

Introduction

Chemical and petrochemical applications often rely on highly efficient and flexible reciprocating engines. Large-scale plants require equipment with greater capacities (a heavier acoustic damping system) or stepless capacity control to improve system performance. Variable flow compressors generate pulsations and vibrations that can lead to element fatigue failure, capacity loss, and associated increased maintenance costs [3].

The cylinder manifold system is made up of the compression system and related dampeners. This system represents the heart of the application, but also can be a source of severe vibrations.

The preliminary cylinder manifold study by GE Oil & Gas has made use of the most advanced simulation methods to assure safety and reliability. Finally, after conducting an acoustic study, a standard cylinder manifold system (CMS) forced response analysis was conducted. This study included the examination of the piping around the compressor and pressure pulsation induced forces so that any problems with the piping supports also could be addressed.

This paper describes a cost-effective procedure that can guide compressor and dampener design from the beginning of a project to help avoid excessive vibrations, assure safe and smooth plant operation, and meet contract project delivery requirements. This is a fundamental target for very complex applications with several stages and many dampeners such as booster-primary low density polyethylene (LDPE) applications.

Description of the Problem

Standard compressor components are dimensioned with a stress analysis that is performed during the machine's design. This analysis defines loads and vibration limits to assure safety and operability. However, the same process is not used for dampeners, whose characteristics vary, depending on the specific application [3]. Additionally, dampener design requires information relevant to the piping plant system, which is usually available only in later project stages.

For this reason it is necessary for all parties to cooperate to meet the contractual delivery date, scheduling in advance the design of critical compression system components (API 618 5th Edition) [1] such as pulsation suppression devices.

Theoretically, these long-term delivery components must be procured after the results of the acoustic and mechanical dynamic analysis that considers the entire scope of supply of the customer's piping plant. Because application schedules are often tight, when customers are unable to provide the necessary information quickly the project contract delivery is jeopardized. In these cases, design risks are sometimes taken in an attempt to stay on schedule. The following new design procedure significantly reduces vibration risks and limits CMS modifications only to the piping supports that are directly connected, without negatively impacting project schedule.

Exciting Forces

Reciprocating compressors generate different types of exciting dynamic forces that may induce:

- High vibration levels
- Poor performance
- Noise
- High risk of fatigue failures

The most significant dynamic forces are described below.

Pressure Pulsation

Pressure pulsation harmonic components, generated by the compressor pulsating gas flow, may produce plant resonance effects when interacting with plant piping and equipment.

Pressure pulsation analysis recommendations can protect plant operations by limiting their effect through a proper damping/filtering system. This study aims to determine a method that limits pulsation amplitude and consequently reduces the relevant induced forces in the compression system, connected piping, and equipment [3, 4, 5].

A thorough understanding of the dampeners' pulsation shaking forces phenomena allows the designer to reduce amplitude by applying known best practices. Shaking forces are generated by geometrical discontinuities in the dampener (for example, a change of direction or closed end). Because it is impossible to avoid such occurrences, the only way to limit their effect is to balance the opposite forces.

The best practice to balance dampener shaking forces is to place the cylinder connection at the center of the dampener. For multiple cylinders, connections should be placed at the center of the chambers by the internal pipes or deviators welded in the shell (see Figure 1). This arrangement creates baffles that divide the equipment into chambers of roughly equal size.

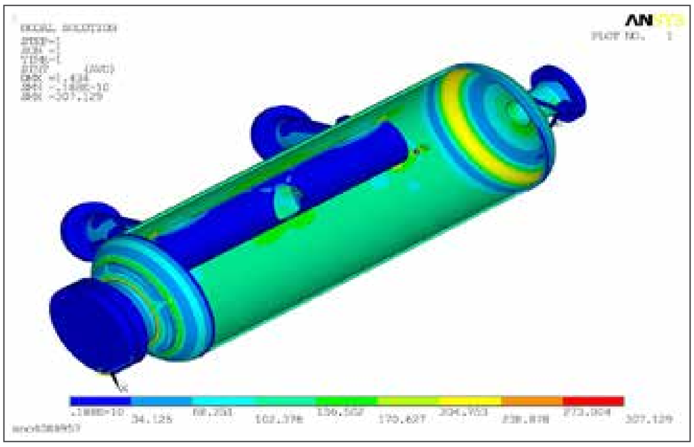

Figure 1. Dampener of two cylinders with deviator

When this type of balancing approach is used, the pulsation induced forces are not critical for the project's vibration design.

Foundation Loads

Reciprocating compressors induce dynamic forces on the foundations due to:

- Centrifugal forces of the rotating masses
- Inertia forces of masses having reciprocating motion
- Torque transmitted by the motor to the compressor
- Couples of various origins

Compressor design strongly influences the forces and moments amplitude, so these factors must be carefully adjusted to reduce their effects. Full balance is generally not feasible – excluding special arrangements – for various reasons (such as type of crank-gear, pistons weights, etc.). As a result, couples acting around the vertical axis are present. After proper balancing, all of these forces and moments define the design of the foundation.

However, loads acting on the foundation are known from the beginning, so the foundations can be properly designed. In conclusion, such forces and moments are usually not critical for the project's vibration design.

Gas Forces Due to Compression

Significant gas forces are generated by compression on cylinder internals. They depend on bore and operating pressures in the cylinder ends under various operating conditions. Being strictly dependent on the data sheet and capacity control system, they cannot be adjusted unless the requirements are changed.

In theory, if the system was rigid (such as cylinder heads and a frame without relative movement), these forces would be balanced/reclosed on the compressor frame. In actual operation, these gas forces can cause "cylinder stretch," which can result in vibration problems. Cylinder stretch occurs as the cylinder assembly lengthens and shortens at the compressor RPM frequency (i.e. first harmonic). With cylinder gas loads' high frequencies spectrum (5th to 10th harmonic components) and relatively large amplitudes compared to pressure pulsation loads, their frequencies may coincide easily with the mechanical natural frequency (MNF) of the compression system, resulting in mechanical resonance phenomena.

For this reason, a detailed dynamic investigation of the effects of cylinder gas loads vibration is an important early project step in guiding compressor general arrangement design. This effort involves a costly preliminary cylinder manifold analysis because the study has to be repeated each time a significant modification is made to the system.

Risk assessment at bid

Complex systems with several different types of forces should be analyzed with care, starting with the selection of the compressor type and its sizing. Although available information is limited during the project bid stage, the first step still can be a risk assessment to advise the customer of potential remedies.

Because mechanical resonances pose the greatest risk, the dynamic design should focus on avoiding such phenomena. System vibration risks are linked to several application characteristics. The following key players should be fully evaluated so that effective remedies can be applied.

Effects of Dimension, Size, Weights, and Pressure

- Large cylinders or compressor-mounted (suction) dampeners involve low CMS mechanical natural frequency, thus requiring reinforced supports on cylinders and/or the suction dampener, with a dedicated foundation or structure.
- For relatively high speed compressors, it is difficult to detune exciting forces from mechanical natural frequencies. A possible remedy involves reinforced cylinder supports and/or a suction dampener on the dedicated foundation or supporting structure.
- Big cylinder bore or high operating pressure may involve high exciting cylinder gas loads that require adjustments to capacity control system selection and/or compressor stages ratio distribution.

Influence of Capacity Control and Variable Speed

- Stepless capacity control can produce several high frequency harmonic components in respect to the standard system with limited steps, such as suction valve unloading. These high exciting frequencies can easily fall in the range of mechanical natural frequencies of the CMS.
- Compressor variable speed results in variable exciting frequencies that can easily fall in the range of mechanical natural frequencies of the CMS.
- Wide operating conditions may produce several resonance conditions due to the amount of exciting forces.

The above factors should be considered to ensure that the capacity control range is limited to the actual needs.

Project Execution

To properly design the compressor general arrangement, it is important to perform a preliminary dynamic analysis of the effects of cylinder gas loads vibrations at the beginning of a project. The cylinder gas loads distribution evaluation and the dampeners selection should represent the first two steps of the design process.

Gas Loads Investigation

Thorough knowledge of operating conditions allows identification of the "worst-case" cylinder gas loads harmonics distribution (Figure 2).

By analyzing the maximum loads spectrum and the conditions that produce high harmonics peaks, the designer can evaluate possible parameter adjustments (such as capacity control steps

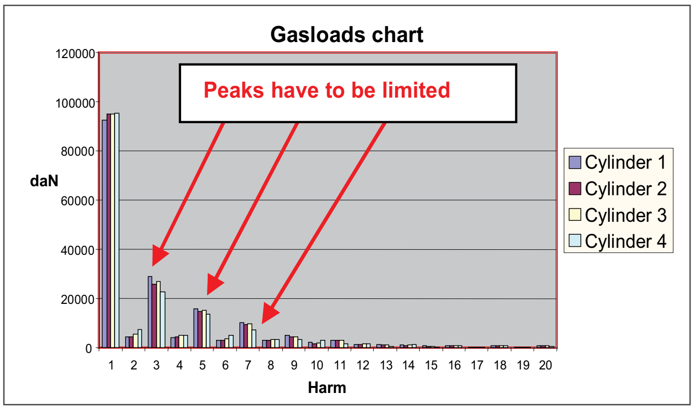

Figure 2. Cylinder gas forces distribution

and compressor ratio distribution). This is done in an attempt to optimize harmonics distribution (by limiting the harmonic peaks) and obtain forces that decrease as a function of frequency increase.

Moreover, to optimize compressor-sizing parameters, this activity makes the designer aware of the amplitudes and frequencies of the forces that need to be controlled to avoid severe vibrations.

Dampener Selection

One fundamental action is the selection of the type (empty volume or filter) and size (volume and piping connections) of the pulsation devices.

A preliminary sizing dedicated program [6] that takes data directly from compressor simulation software calculates the volume, diameters, and length of chokes as well as the relevant pressure drop, optimizing the results for all operating conditions. These basic elements (without dampener geometry) are sized to meet API618 STD Approach 3 allowable pulsations with a sufficient margin (70-80 percent of allowable according to API 618 5th edition section 7.9.4.2.3.4 “pre-study”) [1].

Preliminary General Arrangement Design

The preliminary GA design should begin at project inception, with close cooperation between the compressor manufacturer and vibration specialist.

By taking into account the vibration key players remedy, the initial compression system and dampeners layout design (as shown in Figure 3) can be completed with sufficient accuracy to allow for a very detailed FEM system model. This is done by selecting compressor frame, cross-heads, cylinders, cylinder support, and dampener characteristics.

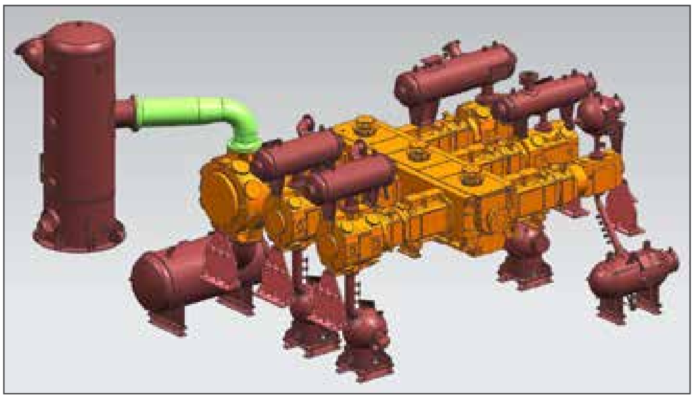

Figure 3. CAD of model Booster-Primary GA

To help ensure that the vessel’s manufacturing schedule can be met, forced dynamic response studies should be performed on the CMS as the project gets under way. This activity drastically reduces the chances of discovering CMS problems later in the project when the impact to the schedule can be significantly larger.

These studies should be repeated when changes are applied to the system during project execution, until the manufacturing process begins. These analyses are used to verify that the vibration levels of the CMS are within allowable limits.

The use of specific software allows the GA designer to comply with the application schedule even without vibration or FEM specialist training. The software helps the designer:

- Perform CMS FEM buildup by selecting compressor standard elements (frame, cross-heads, cylinders, cylinders supports, and so on) and dampener elements by parametric inputs
- Automatically apply the cylinder gas loads resulting from compressor sizing to the FEM
- Run the CMS forced response (without connecting piping) analysis
- Compare the results with allowable vibration limits, remembering that the allowable compressor vibration levels are generally the limiting design criteria
- Change the input data (such as the dampener type or related support data) when the results are above the limits and repeat the study till satisfactory results are found

To achieve satisfactory results, GA designers should work together with vibration specialists. This cooperation is a unique opportunity to enhance their sensitivity to dynamic aspects for a 360° design approach.

Finite Element Model Building

The main step in building a FEM model that is able to simulate the real dynamic behavior of a CMS is to carry out an accurate structural evaluation of the system, with special attention paid to components that affect dynamic performance. When applying suitable simplifications, it is possible to achieve an appropriate balance between accurate and quick calculations. The decision on how to best model the CMS must be driven by the goals that need to be reached.

The most important activity is accurate evaluation of vibration amplitudes. Standard compressor parts are designed with cyclic stresses taken into consideration; loads and compressor vibration limits have been defined to assure safety and operability. However, the dampeners vary with each application, requiring this equipment and its support to be verified for each project.

Based on the above considerations, our study identified a specific structure and element type that allows a good balance between accuracy and calculation speed. Some thin components that are sensitive, dynamic elements (such as dampeners or other parts made from plate metal) were modelled as shell elements.

For thicker elements, such as compressor parts, the super-element technique (see Figure 4) was used. Starting from solid model elements of the frame, sliding body, and distance piece, their equivalent models were prepared and stored in an archive for later selection for specific applications. This allows for a light structure, in terms of computational power, to maintain highly accurate solid element models.

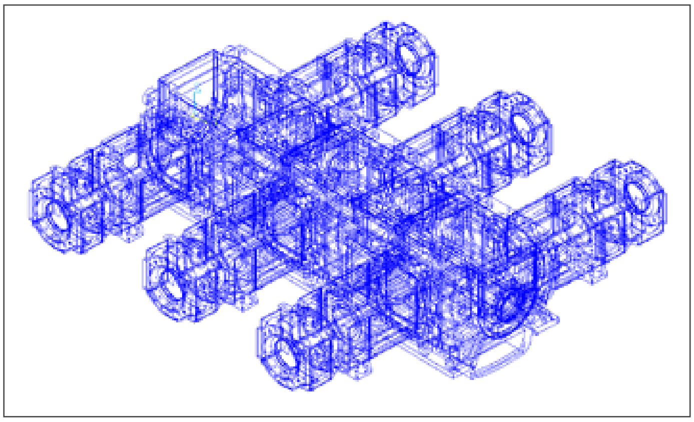

Figure 4. Super-element technique of frame

Compared to other compressor components, cylinders behave more like a rigid body that is sensitive only to its mass distribution. Therefore, they can be treated as solid bodies with infinite stiffness.

Proper modelling of the bolted junctions between the cylinders, distant pieces, crosshead guides, and compressor frame is fundamental to estimating the elasticity response related to connecting different components. A standardized software procedure using manufacturing drawings data (such as number, diameters, length, distribution of the bolts, and flange dimensions) can translate these junctions into the equivalent spring elements needed for proper depiction on the FEM model.

Our chosen approach attempts to balance the required complexity to assure FEM accuracy with ease of use of an enlarged model that includes all significant parts of the CMS. By limiting the computation time, this solution allows the GA designer to quickly test different configurations (for example, dampener layout) to see which provides the most system enhancement. This fundamental software feature allows the designer to use it several times prior to completing system design.

Finite Element Parametric Input Selection

For the above reasons, the input and selection interface must allow for simple parametric input. This means that the user does not need to be a FEM software specialist to build an accurate FEM model.

However, because the creation of the FEM model is a complex task, the software interface should be divided into two main parts: standard parts and specific application elements.

The standard or general parts (shown in Figure 5) allow the user to select and define compressor parts, cylinder support, and dampener type.

Compressor Parts Standardized Selection

The software must include a library containing the compressor super-element models of the CMS standard parts (such as the crankcase, frame, and distance piece). The user has only to select these components and insert the related dimensions using a parametric input interface.

Cylinder and Support Selection

The interface must allow the user to set the type and size dimensions of the cylinders along with the type and dimensions of the relevant supports.

Dampener Type Selection

The dimensions and support arrangement of dampeners varies by application. Standardization, based on experience, allows the selection of a limited set of shapes whose parametric models must be included in the software library. Then the user has only to select the types of dampeners used in each cylinder compressor stage.

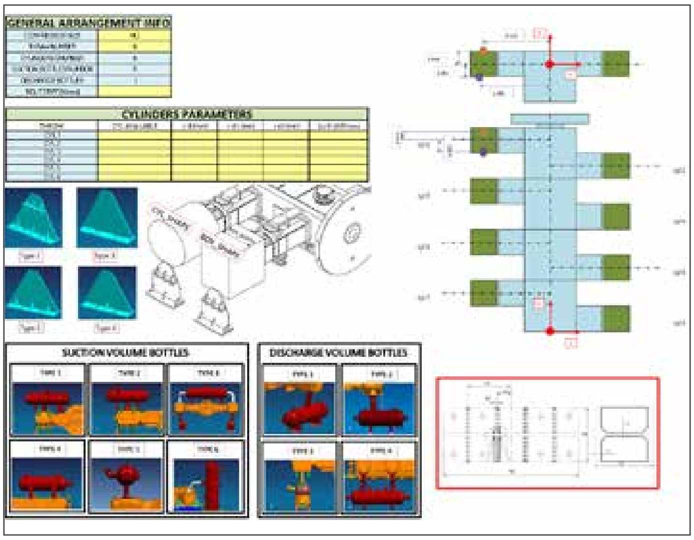

Figure 5. Interface for general parameters

In the second part of the interface, the user inputs the dimensions of each dampener included in the system. Because the dampeners are the most sensitive elements, their definitions are critical for CMS mechanical natural frequencies modal shapes and dynamic forced response. Due to the large amount of detail needed, the compilation of this part of the model is the most time-consuming. For each dampener type, a specific interface (Figure 6) allows the user to set the specific parametric input.

By using specific libraries that contain parametric models and super-element models, the proper simulation of each CMS component can be made. Fortunately, because all of the models are parametric, the user can simply insert the parameters without the need to be a FEM or vibration specialist.

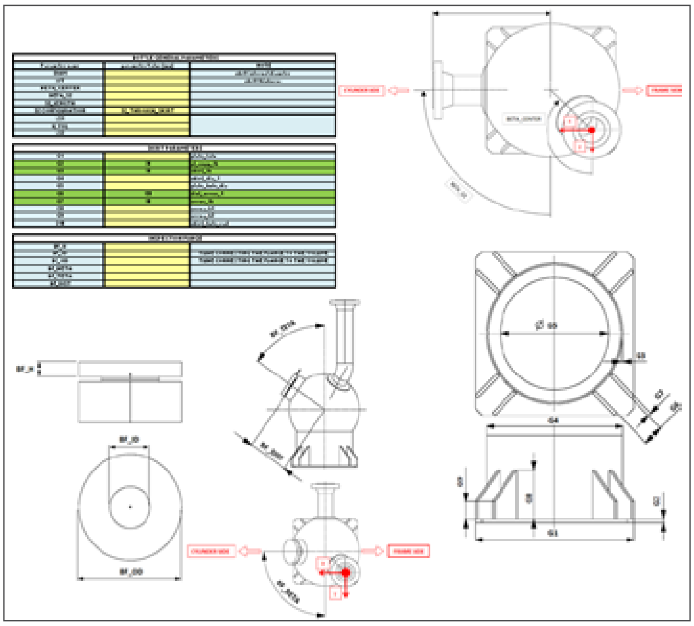

Figure 6. Dampener input table interface

Model Generation

After the parameters have been entered, the user can run the batch process to generate the FEM model (as shown in Figure 7).

The software creates several images of the model that let the user easily verify that the parameters were all entered correctly, or make adjustments as necessary.

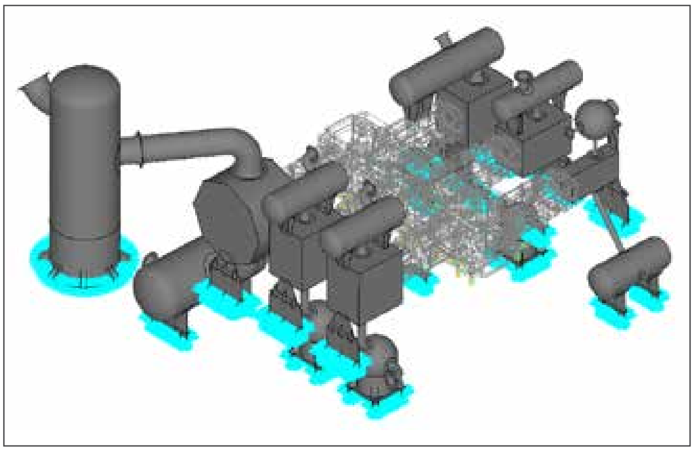

Figure 7. FEM model built by parametric software

Software Dynamic Analysis

Frequency Evaluation

After the FEM model creation process of CMS has been completed and verified, the software can run a batch calculation of the mechanical natural frequencies and store the relevant mode shapes.

The designer first should check that the minimum mechanical natural frequency of any CMS element is designed to be greater than 2.4 times the maximum rated speed (API 618 5th edition para 7.9.2.6.3.2) [1]. All the stored mode shapes should be viewed and their natural frequencies verified. If some frequencies are below the required minimum value, the necessary modifications must be defined to increase the relevant natural frequency (for example, changing dampener support thickness or dampener layout to increase system stiffness).

If it is difficult to identify a necessary system improvement, a vibration specialist may need to be involved in the effort. Once modifications are defined, the parametric input of FEM has to be updated and the calculation repeated until the minimum mechanical natural frequency target is achieved.

Forced Response

Before performing the forced response, the software batch procedure must extract the cylinder gas loads directly from the compressor sizing program archive and automatically apply such forces on the CMS FEM model through the interface.

The software creates some images of the model with red arrows that indicate the applied forces. The designer then easily can control the model to verify that forces have been applied to all cylinders.

Next, the forced response [3] of the system is performed for each harmonic component using the relevant cylinder gas loads (such as the pressure and phase acting on each cylinder axis) as input to calculate the relevant vibration amplitude.

The forced harmonic response is performed for each possible mechanical resonance condition. Through the Campbell diagram (which shows the correlation between mechanical natural frequencies and exciting forces harmonic frequencies) it is possible to highlight resonances that may occur. Usually the analysis is carried out for each harmonic, within a certain percentage variation (for instance, plus or minus 20 percent) of the nominal frequency (RPM).

An important aspect in performing a forced mechanical analysis is the evaluation of the damping coefficient, which is influenced by typical structural material and the connection between components (such as joints and gasket). Standards, piping, and compressor systems typically have damping ratios between 1 and 5 percent, and therefore have amplification factors of 10 to 50. Field experiences indicate that it is conservative to include only the structural damping of the material in the standard forced response analysis. Therefore, when possible (for instance, when measurements are available for an existing application), a damping value derived from field measurements can be used. The model used to evaluate the forced response of the system at a specific frequency is based on the uniform structural damping model; the user can either set this value or leave the 2 percent default value that is stored in the software libraries.

CMS forced response results produced by the batch procedure are:

- An amplitude-frequency chart (Figure 8), which shows if the selected harmonics have vibrations amplitude within the limits
- Several CMS vibration images that help the designer identify vibration locations that are outside the limits (Figure 9)

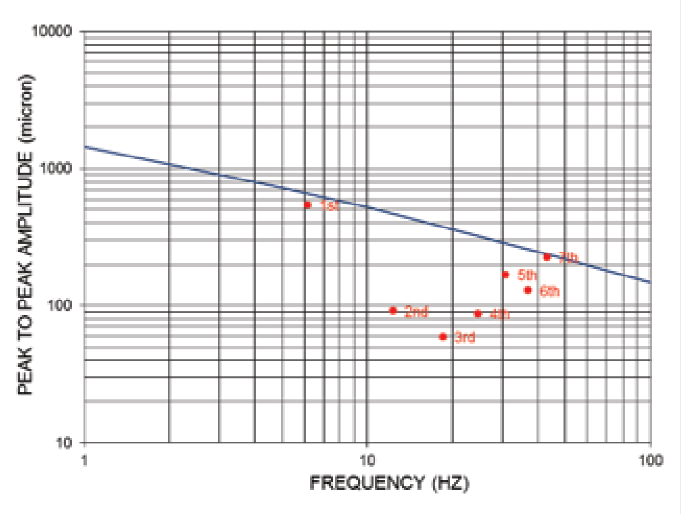

Figure 8. Calculated vibrations vs. allowable limit

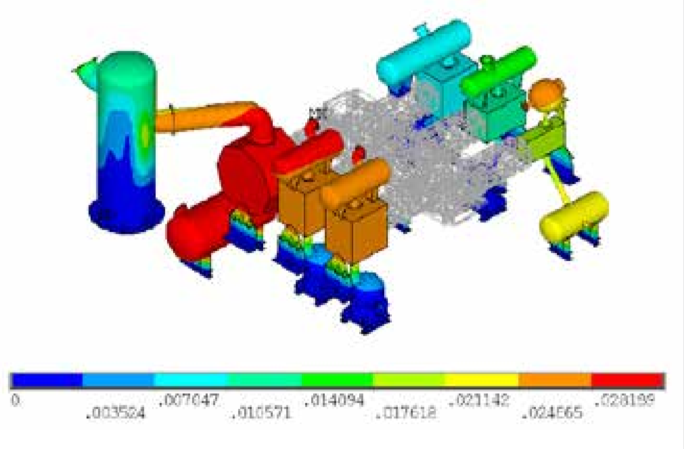

Figure 9. Vibration amplitude

If the amplitude-frequency chart vibration identifies an overcoming limit, the GA designer must view all stored vibration amplitude pictures (usually 21 steps are made to cover the range of +/-20%) relevant to the harmonic components, to define the necessary modifications. Usually, during this phase, vibration specialist cooperation is necessary, especially for complex cases where the simple approach of the system stiffening may not be sufficient to reduce vibration levels to within the limits.

Typical Modifications

The CMS vibration images highlight which components can be critically affected by vibrations. Several modifications can be applied to the system to reduce vibration levels: for example, stiffening the cylinder supports or changing the volume bottle type from single support to double supports (as shown in Figure10).

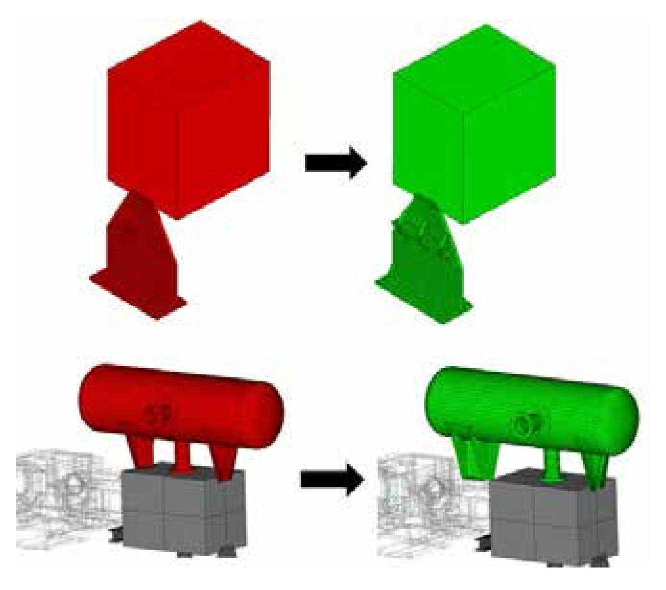

Figure 10: Support stiffening

Once the modifications are defined, the parametric input of FEM must be updated and the calculation repeated until satisfactory results are achieved. When the vibration levels are within the limits, the preliminary vibration design is completed. After the acoustical analysis is completed, the final CMS study must include the piping immediately connected to the compression system to solve any possible issues related to piping supports.

Dampeners Check Prior to Manufacturing

Following the above vibration design validation process, the dampeners (including nozzle orientation and necessary internals to balance shaking forces) are subjected to a pre-study (or "bottle check") with the piping system replaced by an infinite length (acoustically non-reflective line) to verify that the pulsation requirements are achieved with a sufficient margin (such as 70 to 80 percent of the allowable value per API 618 5th ed. para 7.9.4.2.3.4). This approach usually allows satisfactory control of the acoustic resonance conditions that may be discovered during the final pulsation study.

In theory, the procurement of dampeners must be done after the results of the acoustic and mechanical dynamic analysis, including analysis of the customer plant. However, because the customer may not be able to provide the necessary information in a timely manner, the described procedure is the best approach to use prior to dampener manufacturing to avoid vibration risk and keep the project on schedule.

Final Acoustic and Mechanical Piping Studies

Acoustic Analysis

Verifications will take place again after the entire plant system with the final acoustic and mechanical analysis is available, and will be performed considering all possible compressor operating conditions and the capacity control range. All significant components (such as piping, cylinders, valves, orifices, dampeners, coolers, and separators) are analyzed to the proper boundary points. Pressure pulsations and shaking forces acting on the components are calculated at all significant points, reduced to acceptable levels, and used as input for the final mechanical studies.

Piping Vibration and Cyclic Stress

The piping-induced forces (shaking forces) calculated by pressure pulsation analysis are introduced automatically as input data for the plant's final mechanical study. This study is performed by a FEM program that provides the mechanical natural frequencies, total vibration amplitudes, and relevant stresses, along with the reactions at support location.

Then, the overall forced response of the piping system is calculated using the "modal super-imposition" technique as the sum of the response of each mode to the exciting harmonics, each with its module and phase [7].

Finally, the piping maximum alternate stress is calculated using the procedure explained in ASME VIII-2 appendix 5 [2]. The calculated stress is compared with the allowable cyclic stress limit and, if needed, a combination of additional orifices and/or supports can be adopted to maintain cyclic stress within the limit.

Final CMS Forced Response

Finally, the CMS model must be updated considering manufacturing drawings and inserting directly connected piping (generally up to the second support upstream and downstream of the dampeners). Next, the forced response [3] of the CMS is repeated using the following inputs: the exciting forces that result from the pulsation study, cylinder gas loads, and other dynamical loads. This allows the calculation of vibration amplitudes and cyclic stresses, along with the dynamic reaction forces at the constraints.

Results and Considerations

The forced analysis is made to determine the vibration amplitude and cyclic stress.

The vibration amplitude (Figure11) should be compared to the allowable manufacturer vibration levels for the cylinder-frame-spacer block (such as alarm limits with an adequate margin). For the dampener and piping, the relevant limits are based on experience and field measurements.

The cyclic stress (Figure 12) should be compared with the allowable value (API cyclic stress limit 180 N/mm2) [1], reduced to consider the stress concentration factors and safety factor.

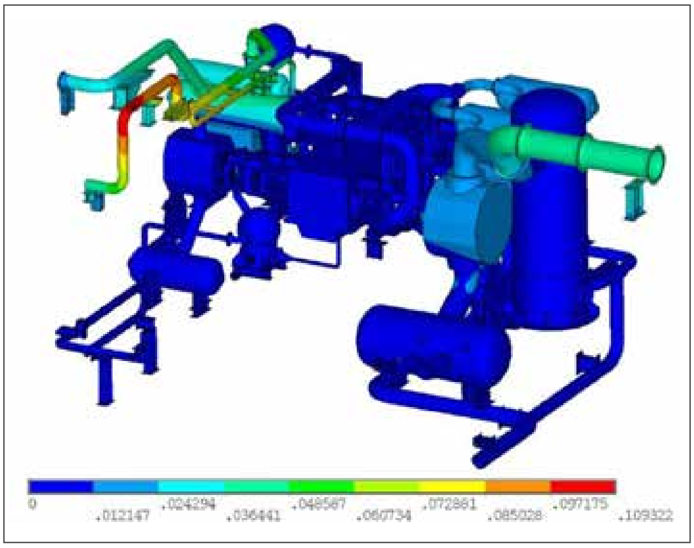

Figure 11. Vibration displacements

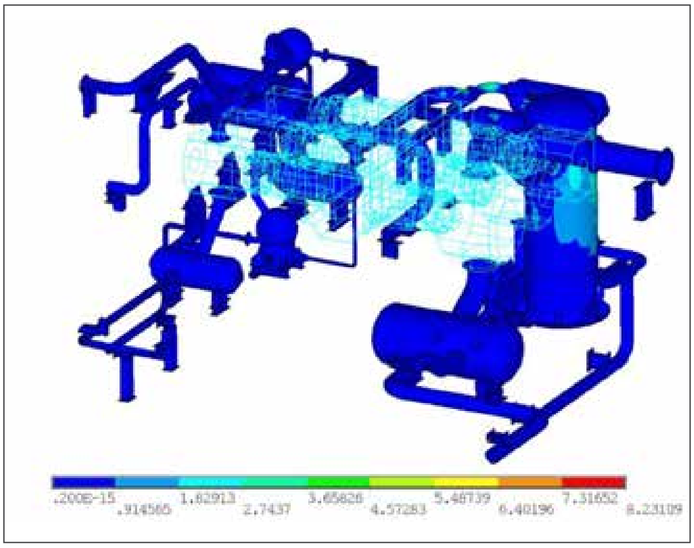

Figure 12. Cyclic stress

Typical Modifications

Several modifications can be applied to the system to reduce CMS vibration levels. However, when the described procedure is applied, the final CMS analysis made after the addition of customer piping can only identify minor piping support adjustments (such as additional piping constraints) and structures (for example, those used to increase the stiffness of the bearing support structure).

Conclusions

Reciprocating compressors and systems that include associated dampeners (CMS) may be the source and location of severe vibrations. For safe and reliable operation, specific analyses are necessary to properly design CMS components from the beginning of the project to avoid major modifications that could jeopardize the delivery date or be discovered when the system is manufactured.

By using best practices related to pulsation-induced force phenomena, the system vibrations can be reduced significantly.

Loads acting on the foundation are known from the beginning; therefore adequate foundations can be easily designed.

Depending on compressor data sheet and capacity control specifications, cylinder gas loads may not be able to be significantly modified unless changes are made to the requirements. Considering their amplitudes and frequencies spectrum, they easily can generate mechanical resonance phenomena.

For this reason, it is essential to use specific software based on an FEM archive of compressor standard elements. The software can complete the CMS FEM by a parametric input of standardized dampener types. To be effectively used by a GA designer who is not a vibration specialist, the software input and selection interface must allow for a straight-forward input procedure to create the FEM model. Finally, the software must automatically apply the cylinder gas loads resulting from compressor sizing, quickly run the CMS forced response, and then compare the results to the allowable values. This procedure must be repeated if changes are applied at the CMS prior to manufacturing.

Later in the project, after the acoustic study is complete, an analysis of the CMS (including the piping around the compressor and pressure pulsation induced forces) must be repeated.

By applying the process as described, the final studies will only require minor modifications on piping supports and their bearing structures, without impacting the project delivery schedule. In addition, the process allows for controllable project costs, reduced vibration risks, and safe, smooth compressor operation.

If, instead, the CMS response study is used only for final verification, the project may be exposed to significant vibration risks. While this latter approach is less costly, the associated risks should be carefully evaluated.

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Imagination at work

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Reciprocating compressor cylinder's cooling: a numerical approach using computational fluid dynamics with conjugate heat transfer
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