Pipeline Applications: Reciprocating Compressor Design Studies

Beta Machinery Analysis (BETA) is the global leader in reciprocating compressor studies (in terms of market share), and has over 40 years of direct experience offering reciprocating compressor vibration, pulsation, performance, field troubleshooting and monitoring solutions. Based on over 10,000 machines analyzed, BETA has accumulated a large knowledge base for the design of new or retrofitted compressor stations, including pipeline facilities.

Three services that are popular with pipeline compressor stations include:

- Compressor Station Performance Analysis
- Pulsation Analysis (per API 618, 5th ed.)
- Mechanical Vibration Analysis for low, medium, or high speed units (per API 618, 5th edition)

There are other engineering services relevant to pipeline facilities, including Foundation Design, Torsional Vibration Analysis, Centrifugal Performance Testing/Monitoring, and Transient Event Analysis. Please contact BETA for information.

1 Compressor Station Performance Analysis: A New Service for the Industry

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, end users 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 end user test the unit and identify if a performance shortfall occurs. Sub-optimal performance represents a significant financial loss.

It is desirable for end users and system designers to have the ability to quickly and economically compare different designs for optimization. End users 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.

The Solution: System Performance Analysis

To address these industry challenges, **Beta Machinery Analysis** and **ACI Services** jointly developed an analysis tool called *System Performance Model (SPM)* ™. As shown in Figure 1.1, the SPM evaluates the complete reciprocating compressor system including cooler, pulsation vessels, separators and all piping. This software is an advanced compressor performance modeling program that is integrated with the total pressure drop data (from the pulsation study) and other design criteria.

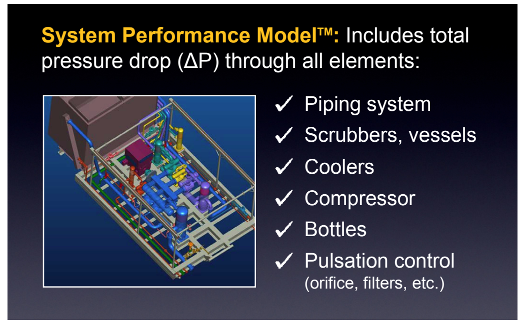

Figure 1.1 System Performance Model (SPM) for reciprocating compressor design

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

1.1 **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 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.

Figure 1.2 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).

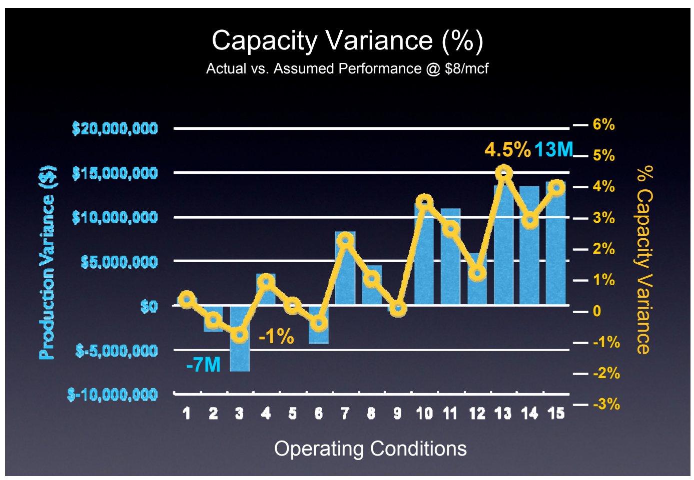

Figure 1.2 Identify Capacity Variance (Actual "System" vs. Initial Assumptions) using SPM analysis software

The SPM ™ software quickly 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.

1.2 Optimize the Compressor Design

API 618 recommends that end users 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 end user.

In this example (Figure 1.3), 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 end user 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.

1.3 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.

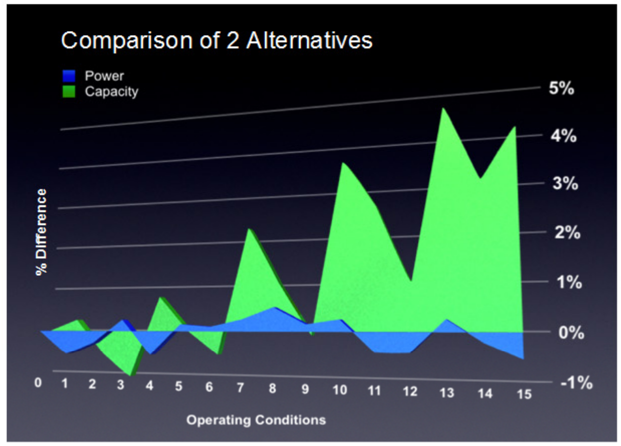

Figure 1.3 Compressor Design Optimization using SPM tool

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.

1.4 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" or "off line". Figure 1.4 shows a facility with multiple units; typical of the projects we regularly work on.


Figure 1.4 Example of a multi-unit facility

1.5 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. Note that pipeline customers using Stoner software, or other pipeline modeling software, will not be able to model the "inside the fence" of reciprocating compressor stations because they do not include the static and dynamic pressure drop and pulsation effects in the piping system. BETA's innovative SPM fills this gap and provides the decision making information for pipeline operators.

2 Pulsation (Acoustical) Analysis per API 618, 5th Edition

BETA works closely with packagers to analyze the piping system and provide a practical pulsation solution. Using our MAPAK™ software, BETA can model many different operating scenarios and types of reciprocating compressors and liquid pumps.

We require accurate drawings to perform a pulsation (acoustical) analysis. Often drawings are available from the end user or compressor packager. In some cases where drawings are not available, BETA can send a representative to site and create the required layout drawings.

We can conduct a pulsation analysis with or without the station or yard piping. Models without station piping can be checked with a specialty termination element. Modeling with this element determines the effects of station acoustic resonances on the compressor package. Using the SPM, BETA can then determine the sensitivity of the package piping to a variety of station piping lengths. If the package piping is strongly affected by the station piping, more conservative pulsation controls can be applied.

Suction system models typically extend from the compressor valves all the way to a large volume (inlet separator) or main header. Interstage models extend from the 1st stage discharge valves through the cooler and back to the 2nd stage suction valves. Additional interstages are modeled the same way. The final discharge models extend from the discharge valves all the way to a large volume or main header.

BETA has the ability to efficiently model multiple units operating together, or various combinations of units. We can also model different compressor models operating through various speed ranges located on the same header systems. BETA has significant experience with storage facilities (injection and withdrawal) as well as with units that can vary the number of stages of compression.

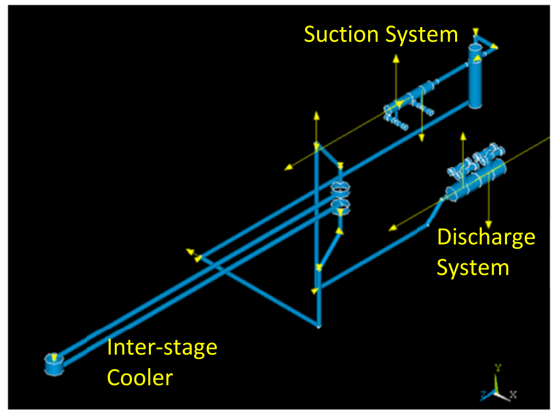

Figure 2.1 Pulsation forces in an inter-stage system, using BETA's Time Domain acoustical solver

Pressure drop created by pulsation controls is an important economic consideration. Too much pressure drop causes reduced throughput, or extra fuel gas consumption. BETA can optimize the pulsation control solution to ensure the end user is maximizing revenue and not incurring excessive operating costs.

One area that distinguishes BETA from others providing similar services is our ability to report dynamic pressure drop, as well as static pressure drop, for all conditions modeled. *Static* pressure drop is the pressure drop due to the resistance of the mean flow between two points. *Dynamic* pressure drop is the pressure drop from oscillating flow introduced to the system by the reciprocating motion of the piston. The sum of the static and dynamic pressure drops is equal to the total pressure drop.

API 618, 5th edition requires that the pulsation analysis consider both static and dynamic pressure drop. The implication is that most commercial pulsation software programs do not meet this standard and employ a much simpler, and less accurate, solver. BETA's non-linear Time Domain solver evaluates both static and dynamic pressure drop (Figure 2.1), and has been in use since 1998.

Another standard characteristic of BETA's pulsation analysis is the full speed range plus or minus 10% to account for variations that may be encountered in the field. Our performance model also predicts BHP per cylinder, rod loads, capacities, meter error, and other performance factors.

3 Mechanical Vibration Analysis (Design Approach 3, API 618, 5th Edition)

While pulsation forces can be reduced through the pulsation solution (as outlined in Section 2), the remaining forces such as gas forces, crosshead forces, mass unbalance and couples, cannot be reduced – they must be controlled through a mechanical vibration analysis. This analysis provides recommendations on piping supports, package design, piping, clamps, skid, and other components.

Mechanical vibration analysis is part of a Design Approach 3 of API 618, 5th edition. The scope includes calculating Mechanical Natural Frequencies (MNFs) throughout the system and a Forced Response Analysis to predict vibration and stress amplitudes, if necessary.

The goal of the analysis is to avoid mechanical resonance in the compressor/piping system. In many situations, and especially at higher order frequencies, it may be impossible to avoid resonance. In this case, the engineer must "manage resonance". Vibration will exist, but through detailed mechanical modeling and Forced Response Analysis techniques, the vibration consultant can predict whether a certain mode or location will have acceptable vibration and stress amplitudes.

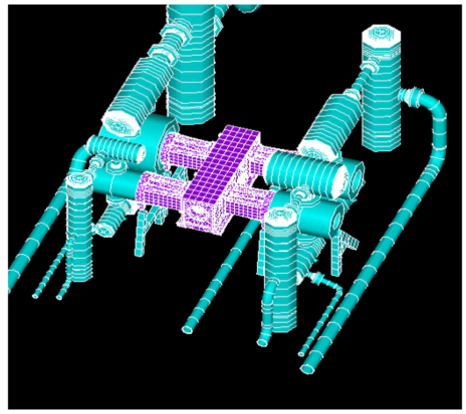

Figure 3.1 Accurate FE modeling, including "super-element" compressor frame

The mechanical analysis starts by developing an accurate computer model of the mechanical system. The model starts at the compressor (or cylinder); includes the pulsation control devices, scrubber, and main piping, and ends, as a minimum, at the second clamp away from the discharge/suction.

To ensure accurate recommendations, BETA has refined its technique and software tools. ANSYS™ is used for all Finite Element Analysis (FEA), because it is the most sophisticated package available for this application. Through our field and design research program, we have created proprietary databases and macros to properly model scrubbers, piping, nozzles, and compressor frames. Figure 3.1 illustrates a mechanical model for a compressor installation. Note that this model includes a (super element) frame FE model to accurately model the boundary conditions of cylinder/piping interface. This super-element frame model is an option for our standard Mechanical Vibration Analysis, and is only available through BETA.

BETA has created detailed 3-D FE models of the vessel and skid to accurately determine the boundary condition stiffness at the base of the scrubber. Figure 3.2 shows a typical scrubber base model. The calculated stiffness is included in the FE model used to predict MNFs.
Cylinder gas forces are very common causes of vibration but, unfortunately, are not yet specified in API 618. To ensure a reliable mechanical design, BETA evaluates gas forces in every project – something not considered by all firms.

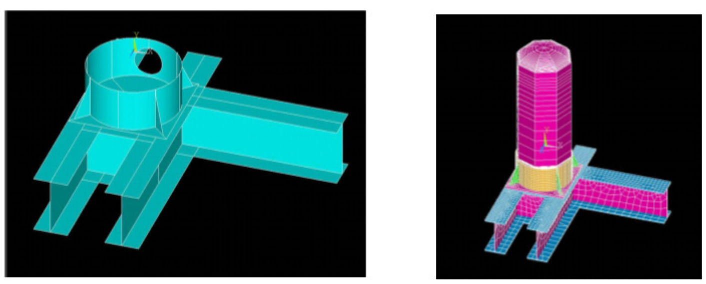

Figure 3.2 FEA includes 3-D modeling of scrubber bases required for accurate boundary condition assumptions

4 Other Studies

The following studies are also common for pipeline customers:

- Foundation design for dynamic loads (reciprocating machines)
- Torsional Vibration Analysis
- Transient Event Studies for bypass and emergency shutdown piping systems
- Condition and performance monitoring for compressors (centrifugal, reciprocating, screw), turbines, engines, motors, and pumps.

Contact our application and support staff for more information on these services. Call 403-245-5666 or email info@BetaMachinery.com.

5 BETA's Software and Analytical Tools

Through a consistent R&D program, BETA has many innovations and software tools to support its engineering services. BETA was the first company to develop digital acoustical simulation tools for reciprocating compressors (project completed in 1973). We revolutionized the pulsation analysis process in 1998 with the introduction of our non-linear Time Domain solvers.

Every year, BETA invests in R&D activities for our analytical tools, such as:

- **MAPAK**™ software package. This is used for Pulsation Analysis for Reciprocating Compressors (API 618) and Reciprocating Pumps (API 674).
- **System Performance Model (SPM)**™ This allows BETA to analyze and optimize the performance of the entire compressor system including vessels, piping, cooler, etc. This tool was co-developed by Beta Machinery Analysis and ACI Services, Inc.
- **Torsional Analysis (Torsan**™) This inhouse program was developed to analyze torsional vibration in the crankshaft, and identify a torsional solution for reciprocating and rotating machine applications.
- **Transient Event Analysis** This study evaluates the transient vibration events in bypass or ESD piping (including water hammer effects).
- **Reciprocating Compressor Analysis (RCA)** This software is used to define the compressor operating conditions, compressor geometry, gas analysis, cylinder gas forces and crosshead forces.
- **DataMiner**™ This software tool enables the customer and BETA to sort through large databases of data to identify key operating or reliability issues.
- **Foundation Design** This service employs commercial software, as well as BETA's own FEA algorithms for analyzing foundations supporting dynamic loads. Our design service involves our capabilities in geotechnical –civil engineering along with machinery design.
- **ANSYS**™ This commercial software is the world's leading program for detailed Finite Element Analysis (FEA). BETA has developed proprietary macros within ANSYS to efficiently and accurately perform detailed mechanical vibration and structural analysis of compressor skids, offshore platforms, and FPSOs.
- **CAESAR**™ This is a sophisticated commercial software package for performing piping flexibility and stress analysis (thermal studies).
- **Performance Analysis** This software evaluates performance on centrifugal, reciprocating, and other machines.
- **Offshore Platforms** ANSYS is used to assess the dynamics involved on offshore platforms or FPSOs.
- **Computational Fluid Dynamics (CFD)** Commercial CFD programs are used for projects requiring more in depth analysis, such as flow conditions.

For more information email info@BetaMachinery.com, call 403-245-5666, or see our website.