Surge Control Dynamic Analysis

For Centrifugal Compressor Systems

By Wally Bratek, P.Eng. and Dr. Kamal Botros, P.Eng.

Introduction

A key goal for operators with centrifugal compressors is to prevent the compressor from going into surge. This is accomplished by proper design of the piping system, associated equipment, and control valves that can balance the opposing requirements associated with start-up, emergency shutdown and normal operation. The dynamic surge analysis (or surge study) evaluates, optimizes, and validates the overall system design by simulating the system dynamic response to these operating scenarios and provides valuable recommendations to the design team. This article explains how an inappropriate piping system design can contribute to a surge event, and outlines the steps necessary for an accurate surge analysis.

A Surge Event Creates Damaging Vibrations

Compression systems are designed and operated to eliminate or minimize the potential for compressor surge, a dynamic instability detrimental to the integrity of the unit. Compressor surge can occur when compressors are subjected to rapid transients, such as the one following emergency shutdown (ESD) or power failure. To prevent this from occurring, compressor stations and their associated piping and equipment ought to be designed in a way to avoid surge, or to bring the unit out of surge quickly if it occurs. The problem is particularly accentuated when a large volume of high pressure gas is retained in the yard piping, including gas aerial coolers.

Figure 1: Centrifugal Compressor Damaged During Surge Event

Once unstable, the unit will experience large flow reversals and pressure transients that cause violent vibration of the compressor rotor, bearings, and casing. Figure 1 illustrates a compressor first-stage failure - one of many compressor problems that have been investigated by the authors. In this case, the compressor damage was extensive and caused considerable downtime.

Figure 2 illustrates an example of results from a dynamic simulation of a compressor system that experienced surge cycles during operation. The Figure shows the unit operating at point “A”, near the surge control line. After the ESD process was initiated, the unit’s performance followed the path toward point “B”. Notice that the flow reverses signifying deep surge due to the effect of high perturbation energy traveling back towards the compressor on the discharge side. The unit’s performance follows violent forward and reverse flows (C to D) until the pressure is equalized across the compressor with no flow through it.

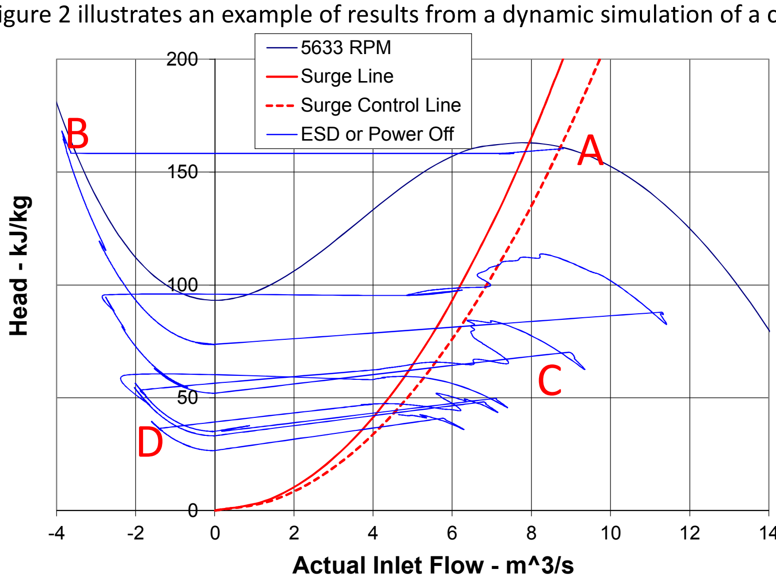

Figure 2: ESD Surge Event (illustrating 5633 RPM compressor instability during surge).

While this event only lasts a few seconds, it will generate violent and potentially disastrous shaking and vibration on the compressor and components.

To avoid damage occurring from upset events such as ESD, a dynamic surge study was performed. After the recommended modifications were implemented, the customer has reported successful results with no surge related problems with the unit.

A surge study is now a common requirement for many systems and particularly crucial to low inertia systems (including the combined compressor/driver rotor system).

The Likelihood of a Surge Event Is Based on Many Factors

The compressor "system" parameters will determine the dynamic response to compressor instability. The likelihood and magnitude of a surge event is based on the compressor's interactions with the following four factors:

1. Physical components, such as piping geometries, vessel volumes, fittings, and recycle and check valve parameters.
2. System inertias (fluid and compressor/driver inertias) because they play an important role in either stabilizing or destabilizing the system dynamics.
3. Compressor performance characteristics, including the OEM supplied surge line.
4. Surge control strategy and timing.

Each of these four characteristics must be evaluated in a Dynamic Surge Analysis.

Furthermore, the recycle system around the centrifugal compressor unit is an essential component in the unit's operation. It is necessary for startup, shutdown, surge protection and flow control (turndown capability) and needs to be assessed with respect to the compressor wheel map.

The most damaging surge events tend to occur during an ESD. As these events are transient in nature, all dynamic parameters from gas flow, equipment, and control, play an important role and impact the system instabilities, performance, and safety.

An Example of Parameters Affecting Surge During ESD

The parameters that affect the potential for the compressor to undergo surge during ESD are the recycle valve characteristics, such as, maximum capacity, flow vs. opening characteristics, opening delay, and valve travel time.

Additionally, timing of the compressor ESD signal, the fuel gas shutoff signal, fuel gas manifold size (in the case of gas turbine drivers), power train inertias, and compressor aerodynamic characteristics close to surge point, all contribute to the complexity of the problem.

Finally, gas and equipment dynamic interactions of other elements employed in compression systems, such as check valves, relief valves, and blowdown systems, are also important and have to be investigated. This leads to mechanical stress analysis, thermal analysis, suction and bypass valve design, and selection criteria.

Avoiding surge is achievable if the above issues are properly considered in the study methodology.

Tips On Software Modeling

Addressing the above dynamic parameters in a surge simulation requires a robust, field proven, software modeling tool. Small details become important when assessing these fast transient events. There are two broad approaches available in the industry, as summarized below.

1. Accurate simulation solver based on the "method of characteristics." This approach employs full Partial Differential Equations (PDEs) and includes the governing one-dimensional equations of gas flow, including the energy equation. Because it includes <u>spatia</u>l gradients, it is considered a distributed parameter based model. Spatial gradients along the length of each pipe segment and around the compressor unit are crucial, as they determine the time taken for pressure, flow, and thermal perturbations to reach one point in the system from another point (e.g., source of the disturbance).

   This approach is effective for numerous transient and unsteady flow problems and is what BETA utilizes in a dynamic simulation tool called CENTRAN. This proprietary model was developed by Dr. Kamal Botros after two decades of experimental and numerical investigations. CENTRAN is a field validated solver and dynamic modeling tool.

2. The other approach is based on commercially available simulators. The limitation of these commercial software packages is that only the time gradients are considered in the dynamic simulations (i.e., <u>temporal</u>). This amounts to describing the dynamics of a system using ordinary differential equations (ODEs), which are much less rigorous than

PDEs and do not include spatial gradients. This approach is referred to as the “lumped parameter” method, which gives a result that is an approximation of the distributed model solution. While this approach is being used in the industry, it is not considered accurate enough for dealing with compression dynamics of recycle systems and surge phenomenon of compressors going into, and out of, surge. Furthermore, they cannot model reverse flows during a surge cycle as that shown in Fig. 2.

Recommended Scope and Specification
When ordering a surge study, the following specifications are recommended. This ensures a complete and accurate analysis will be performed. The study should be performed in the FEED stage, or early in the detailed design stage. This provides sufficient time to review the design and provide recommended modifications to the EPC and operator.

1. Simulation Model. The dynamic model shall include the compressor, gearbox, driver, compressor wheel map, gas composition, discharge volume, start-up time, rotating inertia, delay times, valve response and surge control tuning parameters.
2. Solver. The simulation solver shall employ a robust methodology that includes the full Partial Differential Equations and accounts for both spatial and temporal effects.
3. Recycle system. Assess the recycle system capacity with respect to the compressor wheel map. Confirm the size/capacity (adequacy) of the system for the steady state operating range. Assessment shall include modeling the compressor, piping system and valve characteristics.
4. Startup protocol. Assess the system startup sequence and evaluate discharge temperature versus time.
5. Normal shutdown protocol. Assess the normal shutdown protocol to evaluate the valve shutdown sequence, timing, and rates, and the ramp down of the driver (turbine, motor, engine, etc.).
6. Slow Transient Analysis. Provide an independent check of the compressor surge control protocol during slow transients, such as, inadvertent closure of suction and/or discharge valves (e.g., accidental shutdown).
7. Fast Transient Analysis. Due to ESD, fast stop or power failure, evaluate the entire system and effectiveness of recycle system in severe dynamic conditions.
8. Evaluate interaction between units, where multiple compressors share the same gas path and station piping in series or parallel arrangements.
9. Evaluate additional “what if” scenarios that are often requested by the owner or engineering consultant.

The deliverables shall include recommendations regarding appropriate changes to the control logic, recycle strategy, piping layout, additional equipment and other design aspects, and a report defining surge control characteristics during upset conditions and across the operating window.

End users and EPCs draw on the expertise of Beta Machinery Analysis to conduct this dynamic simulation, as well as other related vibration studies of the centrifugal compressor system, namely Flow Induced Vibration (FIV) and Acoustic Induced Vibration (AIV) studies. Having an independent analysis of the proposed system will ensure an accurate review of the proposed system and practical solutions to achieve the desired performance and safety results.

_ _ _ _ _ _ _ _ _


Wally Bratek

Wally Bratek (M.Sc.) is a Principal Engineer in the Design Group at Beta Machinery Analysis. Wally leads acoustical (pulsation) and mechanical vibration analysis projects on compressor packages and pump installations to meet current API guidelines. He is also experienced in Lateral Rotordynamics, Piping Flexibility Analysis, and Flow Induced Pulsation Analysis. Wally is an active member of the Pulsation Sub-Team, API 618 6th Edition task force, and has been with Beta since 2004. Prior to joining Beta, Wally was a Lead Design Engineer responsible for the mechanical design of turbomachinery utilized in air separation plants. He performed stress analysis on cryogenic turbines and centrifugal compressors, and has extensive field experience including vibration analysis, alignment, and high speed balancing.


Dr. Kamal Botros

Dr. Kamal Botros is a Research Fellow with NOVA Chemicals and a Senior Advisor to Beta’s Surge Control team. Dr. Botros is a world authority on surge control design and analysis, and has focused his research activities on transient flow problems in complex systems including centrifugal compressor surge phenomenon, pressure relief system dynamics, and transients of two phase stratified flows. Dr. Botros has published over 170 technical papers in Journals, refereed conferences, and co-authored this book: “Pipeline Pumping and Compression Systems: A Practical Approach,” published by ASME Press, 2008.