COMPRESSOR SURGE MODELING AND CONTROL

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Biography

Greg retired from Solutia Inc. as a Senior Fellow after 33 years specializing in improving loop performance. Greg contracted as a consultant in DeltaV R&D for 12 years and is presently a Principal Senior Software Engineer in Simulation R&D for Emerson Automation Solutions focusing on dynamic modeling using the Digital Twin. Greg is the author of 80 articles and papers and 20 books. Greg's most recent books are *Advances in Reactor Measurement and Control*, *Tuning and Control Loop Performance 4th Edition*, *Good Tuning: A Pocket Guide 4th Edition*, and *Process/Industrial Instruments and Controls Handbook 6th Edition*. Greg is an ISA Fellow and received the ISA "Kermit Fischer Environmental" Award for pH control in 1991, the Control Magazine "Engineer of the Year" Award for the Process Industry in 1994 and was inducted with Greg Shinskey into the "Process Automation Hall of Fame" in 2001. Greg was honored as one of InTech's 50 most influential innovators for advancing automation and control technologies and received the ISA Life Time Achievement Award in 2010.

Abstract

Axial and centrifugal compressor control is exceptionally challenging due to the extraordinary speed and severity of problems and the extreme consequences in terms of plant safety and performance. The fastest and most dangerous phenomenon is surge. An axial or centrifugal compressor in surge can reverse flow in 0.03 seconds going from a large positive flow to a large negative flow. Often, the negative flow is not measurable by flow meters leaving the actual situation to your imagination.

A high fidelity dynamic real time model has been developed and integrated into a Digital Twin to enable a greater understanding of the special requirements in terms of automation system speed of response and special algorithms. The model uses a momentum balance thoroughly researched and verified. The normally unseen compressor characteristic curve to the left of the surge point is used enabling the model to show the jumps in flow on the positive slopes of the characteristic curve. The unique shape and speed of surge flow oscillations is used in the Digital Twin to explore, develop, prototype, test, justify, deploy, commission and maintain the best surge control system. The Digital Twin also enables not only training of operators but education of process and automation engineers on the extreme dynamics and control system opportunities.

A simple but powerful technique is developed for detecting a potential surge and updating the surge curve. Control strategies are detailed that proactively prevent surge while maximizing compressor efficiency. Unnecessary surge valve openings are avoided and the surge controller setpoint is optimized to lie on the longitudinal axis of efficiency ellipses. Feedforward is used to deal with sudden disturbances from changes in production rates and

shutdown of downstream users. Additionally, a method of optimizing the compressor discharge pressure based on user downstream valve positions is developed. All of these control system opportunities can be demonstrated with the actual control system connected to the model.

Compressor Surge Curve and Setpoint

A surge point is the point on the characteristic curve where the slope goes to zero. The characteristic curve is a plot of pressure rise versus suction flow for a given speed or inlet guide vane position. A volumetric suction flow is typically used because of advantages in terms of being more representative of the operating conditions for surge prevention. When a discharge flow is measured, temperature and pressure compensation are used to get it back to suction conditions. Operation at the point of a zero slope is extremely tenuous because a very slight deviation to the left results in positive feedback and a surge cycle. It is important that the operating point be kept sufficiently to the right on a part of the characteristic curve with a significant negative slope providing some self-regulation by negative feedback (e.g., increase in pressure causes an increase in flow and consequential decrease in pressure).

The surge curve is the intersection of surge points. For a centrifugal compressor, the surge curve is an exponential curve with an increasing slope for increases in flow demand. The ideal surge setpoint should be parallel to the surge curve. This provides a constant operating margin and aligns well with the long axis of the efficiency ellipses. The bias to the computation of the surge setpoint is minimized by making the measurements, surge valves, and PID controller fast enough to react for the worst case disturbance to prevent getting close to the surge curve. Coming off output limits and proportional relative to integral action is optimized.

For axial compressors, the surge curve bends over at high pressures. Also, the consequences of surge tend to be more disastrous because of the higher flows and the possibility of extreme acceleration. One very large compressor would hit a high speed shutdown in a fraction of a second potentially damaging the impeller that cost several millions dollars causing production losses of many more millions of dollars a day. A speed derivative was needed to detect the start of the acceleration and proactively stop the compressor.

Compressor Characteristic Curve and Surge Path

Often not shown is the compressor characteristic curve to the left of the surge point B where the slope becomes positive creating positive feedback causing the suction flow to jump to a negative flow point C on the compressor characteristic that has a negative slope. The operating point then walks along the negative slope portion of the characteristic curve due to negative feedback until it reaches point D the start of the positive slope and positive feedback at which point it jumps to point A, If the surge valve is not sufficiently open, the operating point walks back to point B starting the whole surge cycle over again. The precipitous drop in flow of the first jump can be as fast as 0.03 seconds. Each surge cycle tends to cause a loss in compressor efficiency that becomes noticeable after a total of 10 or more cycles. While successive cycles can be most damaging, the accumulation of cycles at different times is also a concern. The compressor manufacturer may have made tests to identify the surge point but may not have completely detailed the characteristic curves. We will see how surge points can be identified online and a first principle model can provide the characteristic curves to the left of the surge curve in sufficient detail to show the extreme oscillations during surge.

Flow and Pressure Oscillations during Surge

The flow oscillation is characterized by jumps from positive to negative flow and from positive to negative flow that correspond to the path on the positive slope of the characteristic curve creating positive feedback. The walk along the negative slope in the peaks and valleys take about 1 second leading to a total oscillation period of about 2 seconds for plant compressors. For laboratory and pilot plant compressors, the period is 20 times and 5 times faster. The fast periods for all compressors and incredibly fast jumps to very negative flows make recovery by just feedback control improbable.

The pressure oscillations have a period as fast as the flow oscillations but the jumps are slowed down and the amplitude attenuated by the discharge volume of the compressor. The best way of stopping the pressure oscillations is stopping the flow oscillations by an open loop backup that will hold the surge control valve open long enough for system to stabilize.

Compressor Surge Protection and Efficiency Maximization (Vent Valves)

A surge setpoint offset to the right of the surge curve on the compressor map is computed for a suction flow (surge) controller from the pressure rise across the compressor. The output of the PID surge controller goes to redundant vent control valves. The feedback controller is useful to prevent surge for slow approaches to the surge curve but needs help from control logic that is not operating in feedback (closed loop) mode to preemptively position and hold the surge valves open. Since this action is not closed loop and is meant to take over in potentially damaging situations, it is termed an open loop backup. When triggered, the open loop backup puts the PID surge controller in remote output putting the control valves in a position large enough to prevent surge.

The open loop backup must be able to detect surge as soon as possible. This is done by detecting the precipitous drop in flow that is the unmistakable indicator of the start of surge.

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Since a surge cycle is extremely disruptive possibly causing the shutdown of downstream users and each surge cycle counts to a total that causes a noticeable loss in efficiency, it is extremely desirable to predict too close of an approach to the surge curve. This can also be done by the open loop backup. The key component for both recovery and prediction is a deadtime block to create a low noise reliable rate of change signal that can be updated as fast as the PID execution rate. For recovery from surge, a high rate of change triggers the backup that is the input minus the output of the deadtime block divided by the block deadtime that is typically just large enough to provide a good signal to noise ratio. For prevention of surge, a predicted flow one deadtime into the future that is too close to the surge curve triggers the open loop backup. The predicted flow is simply the input to a deadtime block plus the change that is the block input minus its output with the block deadtime set equal to the total loop deadtime. Deadtime blocks can also be used to compute a pressure rate of change for a flow rate of change when operating to the right of the surge curve. A small pressure rate of change for a significant flow rate of change indicates an operating point close to the surge curve.

Turning on external-reset feedback (e.g., dynamic reset limit) enables the use of up and down rate limits on the setpoint the PID is manipulating that does not require retuning of the PID. External-reset feedback prevents the integral action from changing the PID output faster than what is happening in terms of the response to the PID output. This is called directional move suppression. Model Predictive Control greatly benefits from move suppression. By enabling a different move suppression depending on direction opens up many opportunities here and for many other applications. By putting up and down setpoint rate limits on the analog output block for the surge valves and fast readback of actual position, you can have a fast opening surge valve for surge recovery and prevention, and a slow closing valve for gradually returning to a more optimum operating position.

Directional move suppression is also useful for a valve position controller that seeks to lowers the compressor pressure to the point that keeps the furthest open downstream user valve at a good maximum throttle position. Directional move suppression by up and down setpoint rate limits on pressure controller will provide a slow approach to an optimum and a fast getaway for surge prevention. Not shown is a feedforward signal that would be added to the surge flow controller output to proactively open surge valves to a position that would balance a large decrease in flow by a downstream user. The feedforward signal would need to go through a signal characterizer that would compute the change in the X axis (change in valve signal) for a desired change in flow signal per the valves installed flow characteristic.

Compressor Surge Protection and Efficiency Maximization (Recirculation Valves)

The same kind of control strategies shown for vent valves can also be used for recirculation valves. There is a heat exchanger in the recirculation line to prevent heat buildup recirculating flow through the compressor. Recirculation valves are used for multi-stage compressors and compressors in series. It is desirable that stage or compressor have its own surge curve and control system. Decoupling signals can be used as necessary to prevent interaction. Compression rate dividing can be used to provide desired pressure rises for stages and compressors in series. If there are users of intermittent stage or compressor flows, feedforward signals would be applied to the respective stage or compressor surge controller.

Sources of Automation System Dynamics

It is critical that all the sources of delays and lags in a surge control loop be identified and minimized. The deadtime of the actual flow and pressure response (process response) is incredibly fast. The automation system is much slower and must be made as fast as possible to catch up with process response. The control valve often has the slowest 86% response time that is the summation of the pre-stroke deadtime and the rate limited exponential response (e.g., slewing rate with two lags). Signal filtering and transmitter damping must be minimized along with I/O scan times and filters and PID execution rates. Unsuspecting I/O filters are often the main limitation to the speed of response of a supposedly extra fast PID. The default values of these I/O filters may not be accordingly decreased to coincide with faster scan times offered. This mistake and many others are the result of not realizing all the potential contributors to the automation system deadtime that is the summation of all the delays plus equivalent deadtime from lags in series.

How to Make Valve Response Faster

Never replace a positioner with a booster despite age old rules that recommend this for fast loops. This can cause erratic dangerous movement (e.g., slamming shut) of a butterfly control valve from positive feedback due to high and low sensitivity of booster output and input, respectively.

A volume booster should be put on the positioner output with a bypass valve open just enough to prevent fast cycling by enabling the positioner to see some of the large volume of the actuator besides the small volume of the booster inlet port. The positioner should not have integral action and the backlash (deadband) and stiction (resolution) of the control valves must be minimized to less than 0.2% by the use of true throttling valves rather than tight shutoff on-off valve posing as throttling valves with deadband and resolution that can be order of magnitude or more worse (e.g., 2 to 10% deadband and resolution). The entire control valve assembly must be tested for small and large signal changes to verify the 86% response time is always faster than required (e.g., less than 1 second).

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Valve Alerts

The most common mistake is selecting control valves based on tightest shutoff. These have the greatest seat or seal friction and consequently greatest stiction near the closed position. The next is maximizing capacity not realizing that any resolution limit or deadband is a percent of valve capacity and actual rangeability is lost preventing good control near the closed position. The other common mistake is seeking to minimize valve cost not getting the best most precise and responsive throttling valve.

There are many watch-outs. Actuators are often undersized based on thrust or torque requirement for loose packing or room temperature. The actuators should be sized to provide at least 150% of the thrust or torque required for maximum operating pressure and temperature. Resolution and deadband test should be done near the closed position where these effects are greatest (suppliers often choose 40% for testing valve response). The response time should be measured for small steps (e.g., 0.4%) and large steps (e.g., 40%) since actuator and positioner sensitivity and relay capacity come into play for small and large steps, respectively. On-off valves posing as control valves often have a shaft feedback that is not representative of ball or disk position due to friction in seal and packing and play in the actuator shaft to stem and from stem to actual ball or disk connections. A splined connection should be used for shaft to stem connection and the stem should be integrally cast with ball or disk (no connection). If this is not done, the smart positioner is being lied to by its position feedback giving diagnostics and readback that are not real leaving the user clueless.

Boosters should never be used instead of a positioner as previously detailed and integral action that makes the response to medium size steps look pretty, cause poor small and large valve response because the positioner gain needed is less than highest value to accommodate integral action. Also, integral action in the positioner will cause limit cycles from deadband when the surge controller is in automatic and cause limit cycles from stiction even when the surge controller is in manual.

Digital Twin Use and Improvements

The Digital Twin with a momentum balance to simulate the unique and very challenging requirements to prevent and recover from surge and automation system dynamics can be added to understand, design and verify compressor control systems maximize process safety, efficiency and capacity. The extreme consequences of less than the best control strategies and automation system components can be detailed and corrections can be made by rapid exploration and testing. The only limit is your imagination. Online metrics can show the benefits in terms of less loss of compressor efficiency and better process performance.

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Digital Twin's Key New Blocks

Blocks have added to the Digital Twin to test innovations and improvements in strategies, dynamics and PID tuning. The Compressor W/Surge block uses a momentum balance to provide the dynamics of surge. The block can be put in series for multi-stage compressors or compressors in series. A Backlash-Stiction block can be put in series with each other to simulate what is happening in the actuator, shaft to stem connection, and stem to ball or disk connection. Blocks to include a variable deadtime, slewing rate and response lags can be inserted. The Future Value block can provide a timely low noise rate of change and future value typically a factor of the total loop deadtime into the future from current value. This is extremely useful for surge curve and actual surge identification.

Details on Control System Implementation and Best Practices

The principles and knowledge are listed as implementation details and best practices.

Conclusion

This is just a brief insight into the incredible deep understanding gained and great advances possible by compressor modeling and control.

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