INCREASED FLEXIBILITY OF TURBO-COMPRESSORS IN NATURAL GAS TRANSMISSION THROUGH DIRECT SURGE CONTROL

Annual Technical Progress Report
October 2003 — December 2004

Prepared for

U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

December 2004

SwRI® Project No. 18.04990
DOE Award No. DE-FC26-01NT41163

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ABSTRACT

This annual progress report describes the third year's technical progress in a three-year program. This report introduces the benefits of improved surge detection and summarizes what is known about internal flows as surge precursors in centrifugal compressors. Early research results and findings concerning surge in centrifugal compressors and possible precursors to surge are presented. Laboratory test results in modern compressors with 3D impellers are described in detail and used to show the changes in internal flow patterns that occur as a compressor approaches surge. It was found that older compressors with recessed impeller blading (2D geometry) do not have the same accessible flow patterns. The laboratory test results indicate a large increase in potential operating range for modern compressors. This annual report also presents results from the field testing conducted during the course of this third year. The field test results showed similar changes in the surge probe strain signals and the same type, although of less magnitude, of indication that the compressor is approaching surge. An algorithm for identifying the nearness of surge has been proposed and evaluated with the available data.

This project is co-funded by the Gas Machinery Research Council (GMRC) and by Siemens Energy and Automation (Siemens). The results of the project include a step-by-step process for design, sizing, and installation of surge detection probes and for implementation of the direct surge control in centrifugal compressor controllers. This work is considered a step towards the successful implementation of direct surge control for improved flexibility and efficiency in natural gas transmission compressors.

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1. INTRODUCTION

1.1 CENTRIFUGAL COMPRESSORS AND SURGE

Centrifugal compressors constitute a significant portion of compression equipment throughout the energy industry and are a key element for the operation of natural gas pipelines. Simple pipeline style centrifugal compressors are reliable, efficient, and function well when operating near their design conditions. However, flow rates and pressure rise requirements during pipeline operations vary widely and result in compressors reaching various operating limits. A typical performance map for a pipeline compressor, which shows pressure ratio as a function of inlet volumetric flow, is shown in Figure 1-1, which indicates some of the limits on operation of typical centrifugal compressors. Maximum speed, discharge pressure, or power limits occur at the top of the map where the pressure rise required reaches a limit for the compressor. The high flow or stonewall limit is reached on the right side of Figure 1-1, and the minimum stable or minimum driver speed is reached at the bottom or low pressure rise (low head) area of the compressor map. The limit for low flow operations is set by a flow instability known as surge, which is expected to occur along the low flow limit shown as the solid line on the left side of Figure 1-1. The exact location on a compressor map at which surge occurs is not normally known and is affected by many factors, including gas composition, piping configuration, and parallel operating units. As a result of this uncertainty in the external conditions at which surge will occur, a surge control line is usually estimated and placed on the map as shown in Figure 1-1. The surge control usually has a 10% of design flow margin above the expected surge line as shown by the dotted line in Figure 1-1. With no other indication of when surge will occur, a compressor's flow is usually maintained at or above the surge control line by recycling flow in order to protect the compressor from surge.

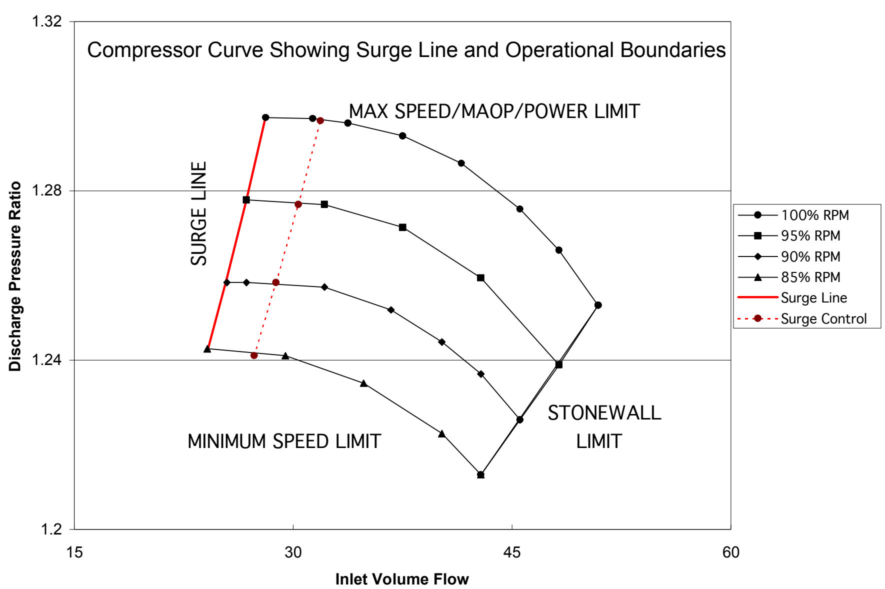

Figure 1-1. A Typical Compressor Performance Map Showing the Limits of Operations Including the Surge Line and the Surge Control Line

Surge is a complete breakdown of the flow pattern within a centrifugal compressor's impellers and passages, which results in a reversal of flow through the compressor. This global collapse of flow through a centrifugal compressor results when too little flow is being forced against more pressure rise than the compressor can generate at that operating condition. Surge usually occurs suddenly and with little warning, although in some, but not all cases, unsteady pressures and vibrations that are due to stall or off-design operating conditions precede surge. The pressure variations and vibrations that are seen before surge in some cases are not fundamental indications of approaching surge and can occur well before surge is imminent or not at all prior to surge. When surge does occur, both flow rate and head decrease rapidly and gas flows backwards through a forward spinning impeller, which causes large dynamic loads on thrust bearings, blades, and other components of the compressor. Surge at full speed and head is a dramatic and violent event that disrupts throughput, can cause damage to a compressor, and often results in significant downtime. Surge during normal operation should be avoided.

1.2 INTENT AND BENEFITS OF DIRECT SURGE CONTROL

Surge avoidance is essential for pipeline compressors and is normally achieved by recycling gas around the compressor to maintain a flow no less than the surge control flow rate. Recycling flow is achieved through a pipe connection (recycle line) that carries some discharge gas back to the suction through a restrictive control valve known as a recycle valve. Recycling flow lowers the pressure rise (head) the compressor can generate, consumes extra fuel or power from the driver, and significantly lowers overall efficiency. If the actual approach of surge could be detected, then the centrifugal compressors could be operated with less recycled flow and a higher overall efficiency. The purpose of the current direct surge control development is to use an internal measurement to control centrifugal compressors close to surge in order to increase operating range, reduce surge margins, use less recycle flow, and hence increase operating efficiency.

1.3 EARLY GMRC AND OTHER RESEARCH

In the early 1980's, the Gas Machinery Research Council (GMRC) funded research at Southwest Research Institute® (SwRI®) to study the processes involved in surge. At that time, there were no known or reliable precursors to surge, although a number of signals and theories had been tried. The early GMRC research eliminated many changes in compressor flows and conditions as indicators of surge. Tests in the early work showed that the vibration and pulsation indicative of off-design operation do not always occur prior to surge and are caused by other mechanisms rather than by near surge conditions. One change was found that does indicate the approach of surge in small laboratory compressors and that change was a re-circulation in the outer portion of the impeller inlet. This observed impeller inlet flow re-circulation pattern has subsequently been verified in other laboratory and field compressors and has been reported by other authors[1,2].

In the early GMRC funded research, the inlet area of the small laboratory compressor was instrumented for flow direction and magnitude. The only significant change observed as the compressor approached surge was a reduction in magnitude of velocity along the outer diameter of the impeller inlet. This reduction in local flow was significantly greater than the reduction in average flow. The outer ring of the inlet flow field also develops a tangential component in the direction of the impeller rotation as flow rate was reduced. Figure 1-2 is a plot of the inlet flow in the direction towards the impeller measured with a bi-directional pitot type probe along the outer wall of the inlet passage, and shows that the flow along the outer wall reduces rapidly, reaches zero, and begins to flow backwards as surge is approached. The data shows that the flow recirculation occurred only in the outer diameter area of the impeller inlet. The temperature of the gas in the outer diameter area was observed to increase during the recirculation. The signal in Figure 1-2 would be useful as a surge avoidance and control signal if this change can be measured in field compressors. The development of a recirculating flow pattern at the inlet of a centrifugal compressor impeller is an indication of approaching surge.

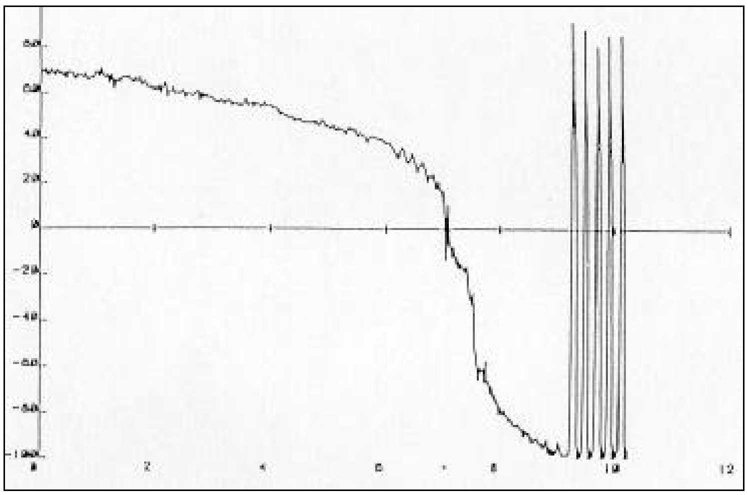

Figure 1-2. Pre-Surge Change in Impeller Inlet Flow along the Outer Wall of a Small Laboratory Compressor during Early GMRC Research.

2. EXPERIMENTAL

2.1 LABORATORY TESTS OF PRE-SURGE DETECTION

The first laboratory compressor was an old style pipeline compressor with a 2-dimensional (2D) impeller. The results from this test do not show the inlet re-circulation that indicates pre-surge conditions. These tests do show that the drag probes are rugged and reliable, and indicate the flow changes at the impeller inlet. However, the inlet flow changes were not those expected or sufficient to indicate any approaching surge.

Testing conducted in a laboratory compressor with a modern 3D impeller did show a clear indication of the strain signals that result from flow re-circulation and a direct measure of the approach of surge. The first 3D laboratory compressor results shown in Figure 2-1 were taken at a relatively low compressor speed of 13,100 rpm during a slow approach to surge, which occurred over a period of approximately 30 minutes. The data from this test shows that the axial strain follows the decreasing flow at first, then increases to a local maximum, and finally drops rapidly to a negative value as flow is reduced towards surge. The tangential strain during the same approach to surge remains near zero in the normal compressor flow range and then increases significantly as the low flow near surge condition is approached. A scaled flow signal, that is inlet flow rate divided by an arbitrary constant, is shown in Figure 2-1 to indicate the decreasing compressor flow. The second laboratory test results included in Figure 2-2 show the same pattern of axial and tangential strain changes at a compressor speed of 16,000 rpm during a rapid approach to surge that occurred within a two-minute time frame.

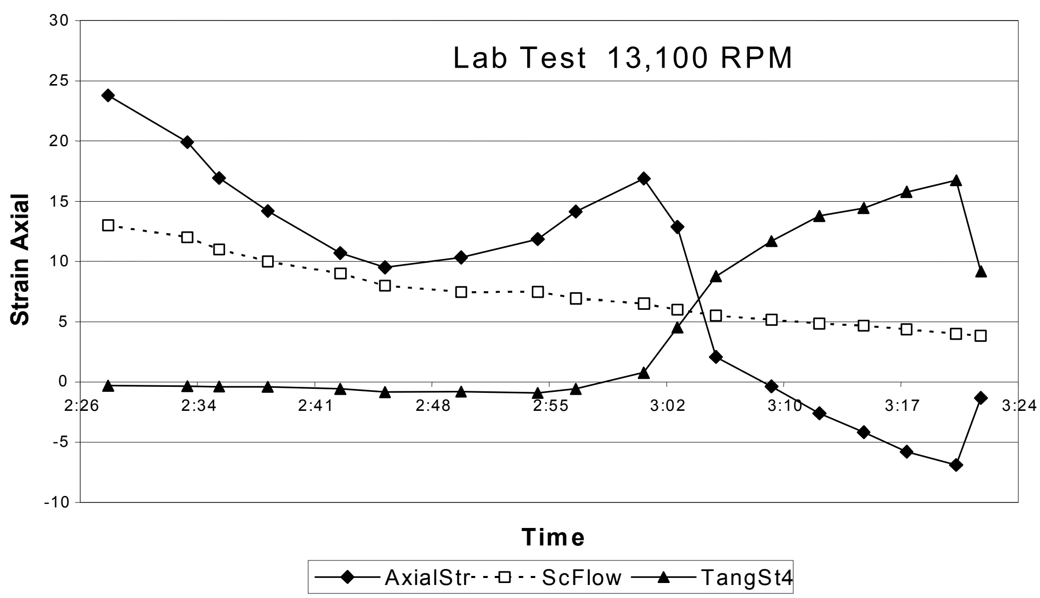

Figure 2-1. Axial and Tangential Strain Changes as Scaled Flow Decreased Towards Surge in a Modern 3D Laboratory Compressor at Low Speed

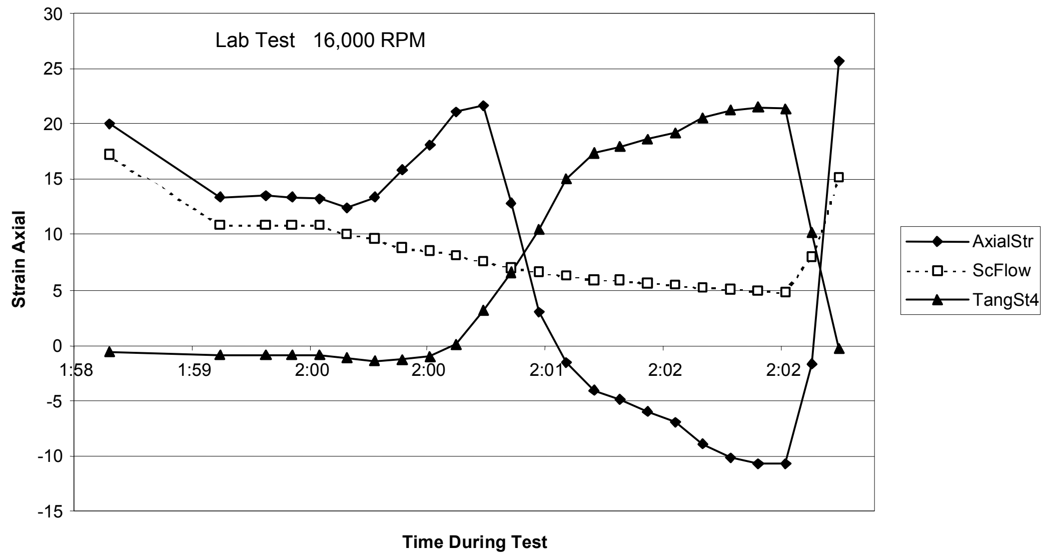

Figure 2-2. Axial and Tangential Strain Changes as Scaled Flow Decreased Towards Surge in a Modern 3D Laboratory Compressor at Moderate Speed

The third set of modern (3D) compressor test data was recorded at a relatively high speed of 19,200 rpm as flow was lowered towards surge. The same pattern of axial strain decreasing with flow, experiencing a local maximum, and then rapidly decreasing, and the tangential strain remaining unchanged and then significantly increasing as surge was approached is shown in Figure 2-3. The duration of the test was approximately two minutes showing that these re-circulating flow signals occur during rapid changes as well as during slow approaches to surge. In addition, the changes in flow induced strain signals appear to be essentially the same at low and high speeds. Figure 2-4 shows the compressor map from the modern laboratory compressor direct surge test and shows that the compressor was able to operate over a significantly wider range of flows than expected for this type of compressor. This increase in operating range represents a region of compressor flows and heads that can be achieved without recycling flow and hence without wasting fuel and operating cost. The large increase in operating range in Figure 2-4, approximately 20% in turndown, may not be typical of most pipeline compressors, which may have smaller potential gains, but is indicative of the improvement in compressor flexibility and efficiency that may be achieved.

2.2 Final Field Test Results

Testing of a prototype direct surge control system has recently been conducted in a modern 3D natural gas pipeline style compressor. This testing and refinement of the surge control system and surge control algorithms in the controller are continuing at this time. Some of the early results of axial and tangential strain as flow is reduced towards surge are shown in Figures 2-5 and 2-6. In this data, flow decreases as shown by the scaled flow line, axial strain decreases at the same rate as flow, and tangential strain increases during the normal part of the compressor operation. As the flow reaches a lower value approaching surge, the axial strain

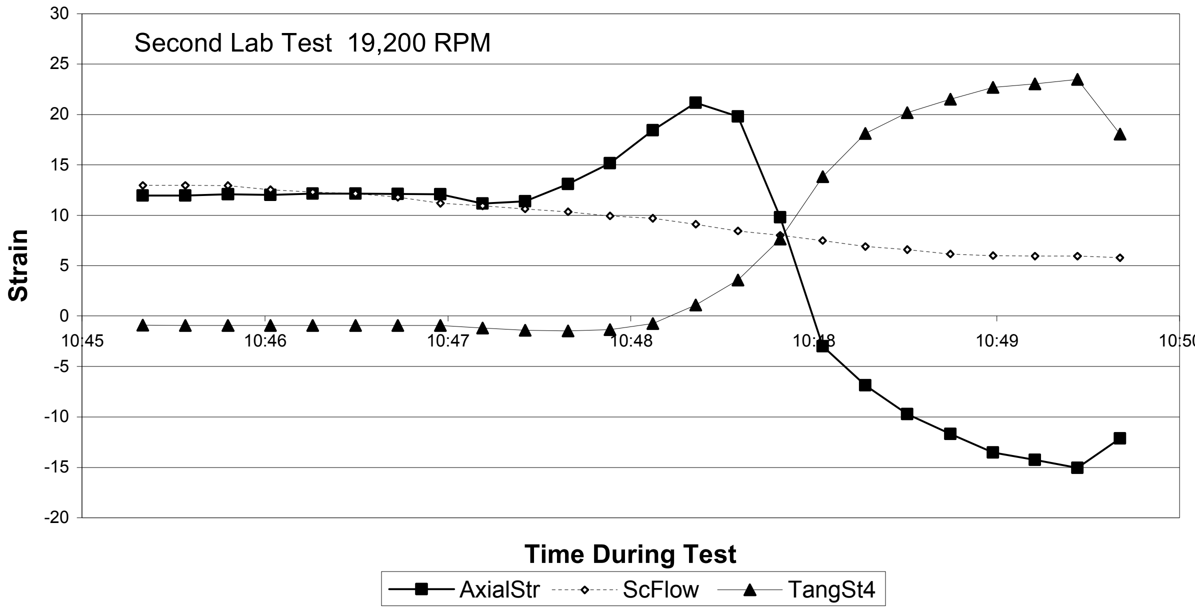

Figure 2-3. Axial and Tangential Strain Changes as Scaled Flow Decreased Towards Surge in a Modern 3D Laboratory Compressor at High Speed

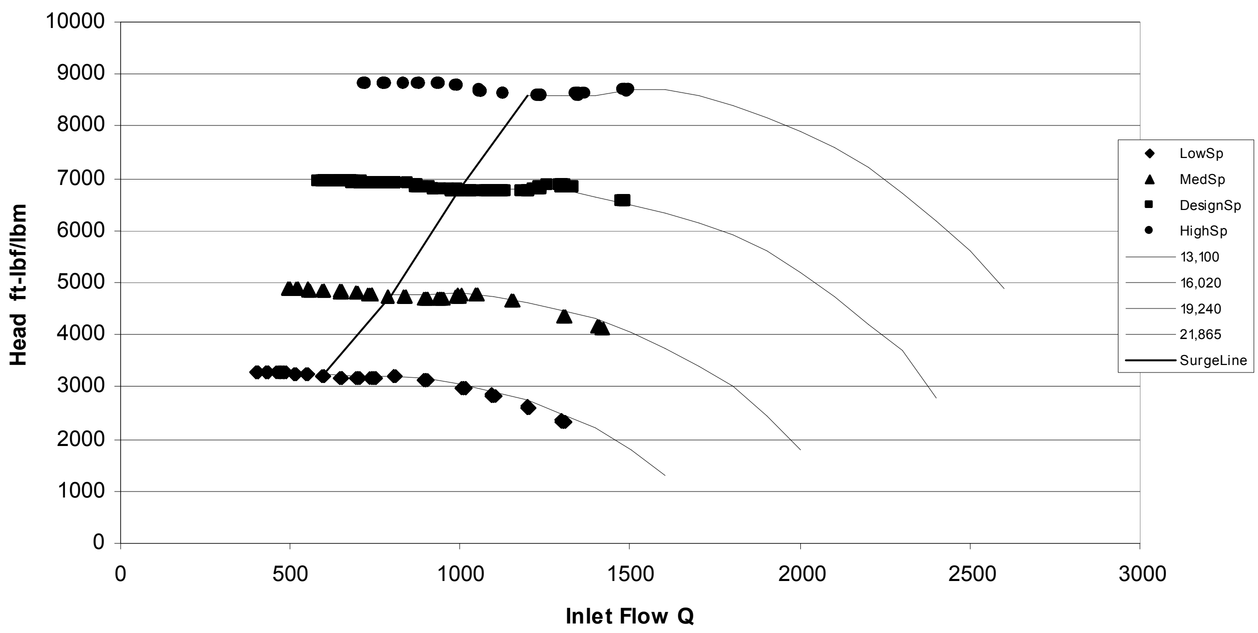

Figure 2-4. Stable Operating Points During Surge Detecting Testing Showing a Potential Increase in Range and Turndown Using Direct Surge Control

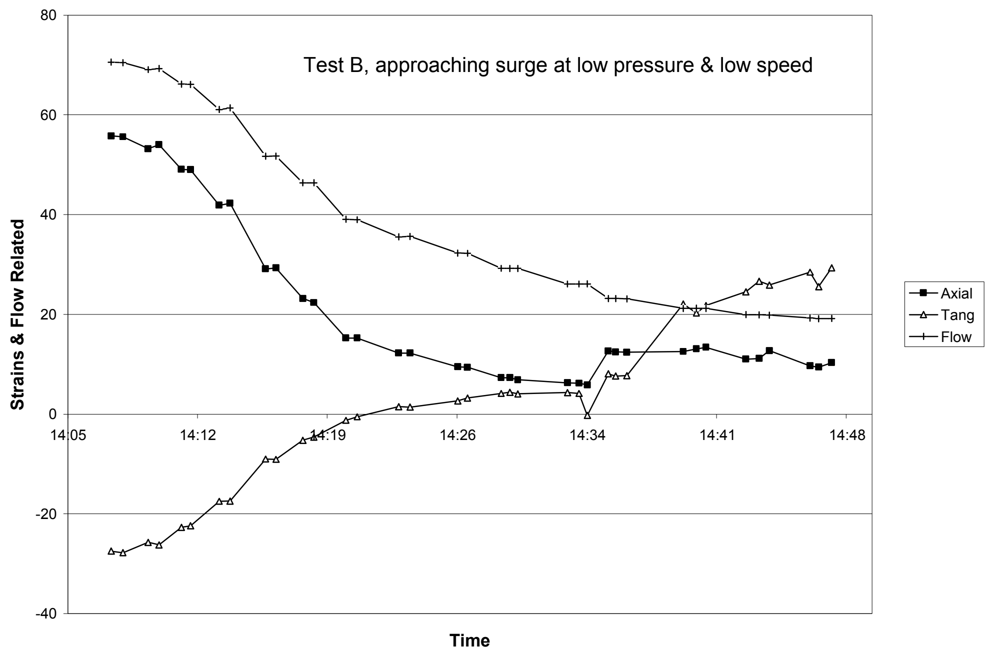

Figure 2-5. Axial and Tangential Strain Changes as Scaled Flow Decreases Towards Surge in a Modern 3D Pipeline Style Compressor, Test B

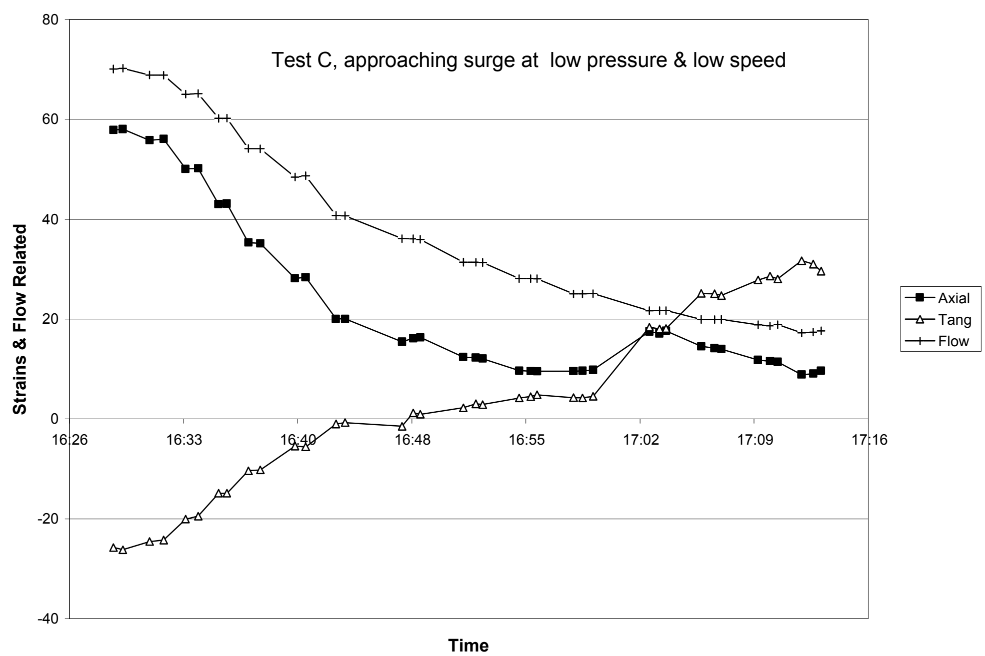

Figure 2-6. Axial and Tangential Strain Changes as Scaled Flow Decreases Towards Surge in a Modern 3D Pipeline Style Compressor, Test C

increases through a local maximum and then decreases slowly while the tangential strain starts to increase rapidly. These changes in the flow induced strain, as surge is approached, result from the developing re-circulation even before the flow changes reach the probe location and from the tangential components of the flow before surge occurs.

A third set of results is shown in Figure 2-7. The flow rate in Figure 2-7 is shown by the differential pressure in inches of water while both the axial and tangential strain signals are shown on the same scale in units of micro-strain (micro-inches per inch). The changes in strain signals in Figure 2-7 with the axial strain decreasing with flow, experiencing a local peak, and then slowly decreasing, and the tangential strain slowly increasing until it rapidly increases as surge approaches is the same as in Figures 2-5 and 2-6. The strain signals in Figures 2-5, 2-6, and 2-7 are slightly different from the strain signals in Figure 2-1, 2-2, and 2-3, which are from the laboratory rather than the field compressor. The installation of the drag probe in the natural gas compressor, where the probe is overhung from the inlet wall, is somewhat different than in the laboratory compressor where probe penetrates the inlet wall perpendicular to the flow. There appears to be small differences in the resulting pattern of the strain signals that is dependent on the details of the probe and compressor geometry.

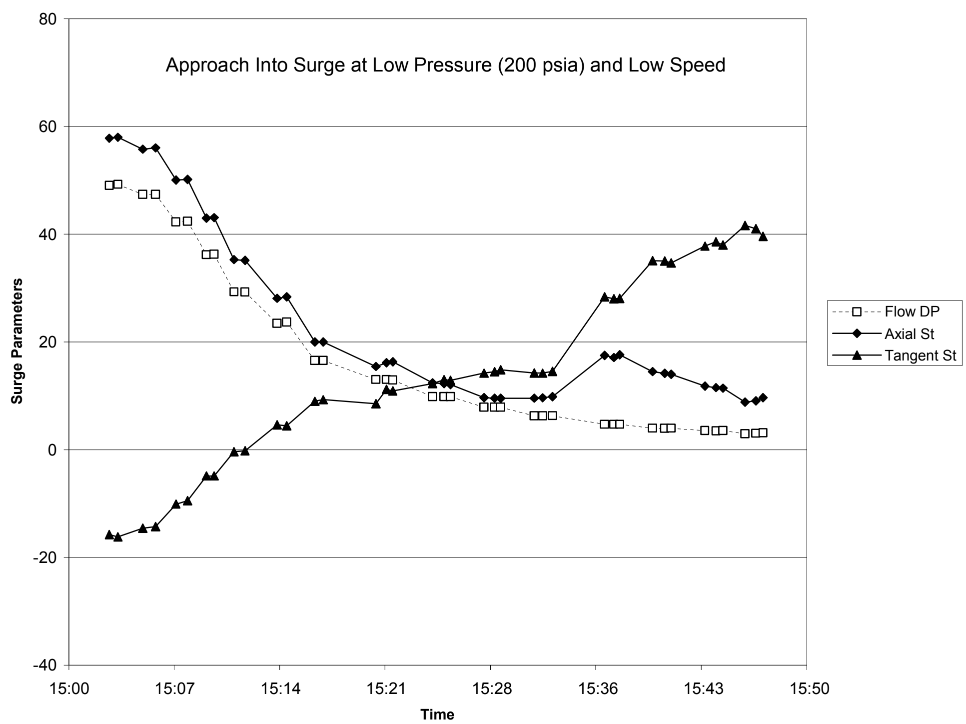

Figure 2-7. Axial and Tangential Strain Changes with Flow DP as Surge is Approached in a Modern 3D Pipeline Style Compressor, Test E

There are many approaches to tracking the relative magnitudes of the axial and tangential strains to determine if surge is approaching, including identifying the rapid decrease in axial strain and the increase in tangential strain, monitoring the slopes or derivatives of these signals, or other combinations of strain changes. With the dependence of the strain signal details on the probe location in the compressor geometry as shown by the two modern compressor test results, a method that is reliable despite small changes is required. If the difference between the two strain signals, that is, the axial minus the tangential, is taken, then the dependence on particular features of one or the other signal is reduced. During the most recent tests, the stability of the strain signals has been sufficient that a comparison of the values is reliable. If the drop or zero crossing of the axial strain is not significant as a pre-surge indication, then the increase in the tangential component can be used to emphasize the drop in the axial flow. Each compressor can be expected to be slightly different, but with the proper algorithm, the approach of surge will be identifiable. Figure 2-8 shows the difference in the strain signals for each of the six tests in Figures 2-1, 2-2, 2-3, 2-5, 2-6 and 2-7 as a function of a scaled flow rate. The low positive values, zero crossing, and negative values of these signals could easily be used to detect and control the approach of surge.

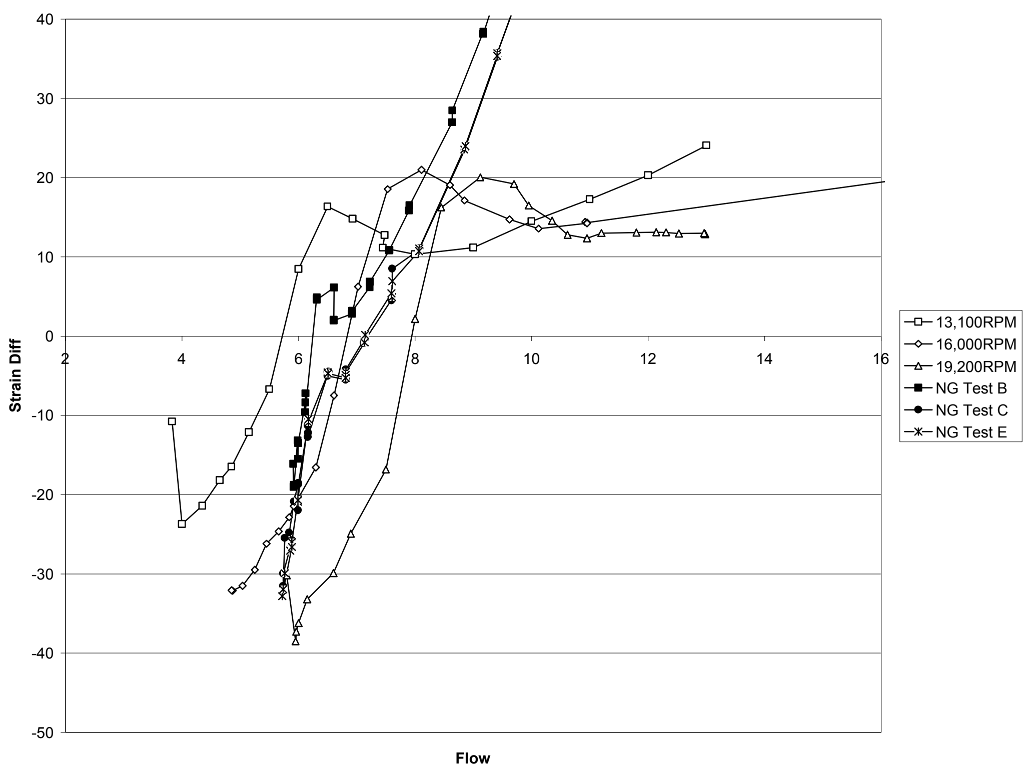

Figure 2-8. Plots of the Axial Minus Tangential Strain Difference for Six Different Tests of Modern Compressors Approaching Surge Showing a Negative Difference Before Surge.

3. RESULTS AND DISCUSSION

The steps necessary to retrofit an existing compressor with a direct surge control system have been defined during this project and are shown below. Installation of a direct surge control system in a new compressor during the design and manufacturing process would be a relatively easy subset of these steps.

- Determine if the compressor has a modern 3D impeller with blades at the front face of the impeller. If the impeller has 2D blades in which the leading edge of the blades is recessed from the impeller inlet, the current approach is unlikely to be successful.

- Calculate the flow velocity range and gas density range from the performance map and operating conditions of the compressor. The inlet geometry of the impeller, including the inlet face smallest (hub) and largest (outer blade tip) diameters is required for this calculation.

- Size the drag body that will be located along the outer wall of the inlet passage. The drag body should extend into the inlet channel by considerably more than the boundary layer thickness, but by no more than a quarter of the channel height (distance from inner to outer radius). A size of 8% to 15% of the channel height is a good starting point, with the understanding that in small passages a height of more than 20% may be necessary, while in large channels, 5% may be sufficient. The total cross-sectional area of the probe should be no more than 2% of the total inlet flow area, and the diameter of the drag body can be set from this and from practical considerations of penetration hole diameter, other geometry considerations, and manufacturable sizes. If the impeller inlet has several individual channels or passages between inlet guide vanes, then the probe should not be so large as to excessively block an individual channel or passage. In general, the height and width of the drag body should be of the same order of magnitude.

- Calculate the force on the drag probe from the drag coefficient times the velocity pressure and cross-sectional area of the probe. The velocity pressure in a flow is the density times the velocity squared divided by two times the gravitational constant (e.g., $\rho V^2/2g$). The drag coefficient for a circular cylinder, the shape used for these drag probes, is approximately 0.5 at the high Reynolds numbers of inlet flows.

- The probe's bending beam width and length are then determined. The bending beam will generally have a square cross-section, and the width can be wider for strength and narrower for sensitivity, but must accommodate the strain gauges to be used. The bending beam does not need to be exposed to the flow, but must be attached to the support or restraining piece.

- The strain expected from the strain gauges placed on the bending beam is calculated. Strain gauges are used in pairs (on opposite sides) at the support end of the bending beam to generate the maximum strain per unit force and to produce a null strain due to thermal expansion or contraction.

- Calculate the mechanical natural frequency of the probe on the end of the bending beam and calculate the vortex shedding frequencies due to flow over the drag body. Check that the mechanical natural frequency does not correspond to the compressor running speeds or any of several higher orders of compressor speed such as blade passing frequencies. This step also confirms that the vortex shedding frequencies are above the expected surge and sub-synchronous stall frequencies of a few to several Hz and below the mechanical natural frequency of the probe over the full range of expected flows.

- Design the probe holder or support to attach the probe to the compressor's stationary parts, to position the drag body along the outer wall of the inlet passage as close as practical to the impeller, to allow for the length of the bending beam, and to retain the probe and provide a rigid support. The other part of the physical design, which must be considered at this stage, is a means to allow the signal wires to exit the compressor.

- Checking the results of the design so that the probe is not too large for the inlet passage, experiences a reasonable force at near-surge flow conditions, will not fail or deform at extreme flow conditions, will not vibrate due to compressor or flow excitation, is located correctly along the outer wall of the inlet passage near the impeller, and can be supported firmly in the compressor. If these conditions are not met, repeat the design process from the third step and adjust the factors to improve the flow sensor's parameters and overall performance. The above design steps are iterative and several adjustments to the size, the bending beam, and the supports may be required until the probe is strong, sensitive, and vibration-free. In general, a drag probe is an adaptable and versatile device that can be designed for the specific compressor geometry and operating conditions. A drag type direct surge probe, which resulted from this design process, is shown in Figure 3-1.

- The final step in the design of the probe involves arranging for signal wires to pass from the probe to the outside of the compressor case where the signals can be monitored. Arrangements for the wires and the signal from the probe to exit the compressor pressure case through a safe, leak proof, and durable fitting or connection that does not invalidate the hydro test and pressure rating of the compressor case is an essential design step. The probe is located on the suction side of the impeller, and signal wires may have to be routed through an internal division wall, a flow guide, or other internal compressor structure, but will generally be in the suction cavity of the compressor. The signal wires may penetrate a drain plug or an existing threaded pressure tap, a flanged pressure cover or plate used for a control device penetration, or as a final option can be routed into the suction piping and through a pipe pressure tap. The strain gauges and wires on the probe are coated for protection, and the wires are run through well secured conduits or metal tubing for protection. The final wiring design involves many details unique to each model

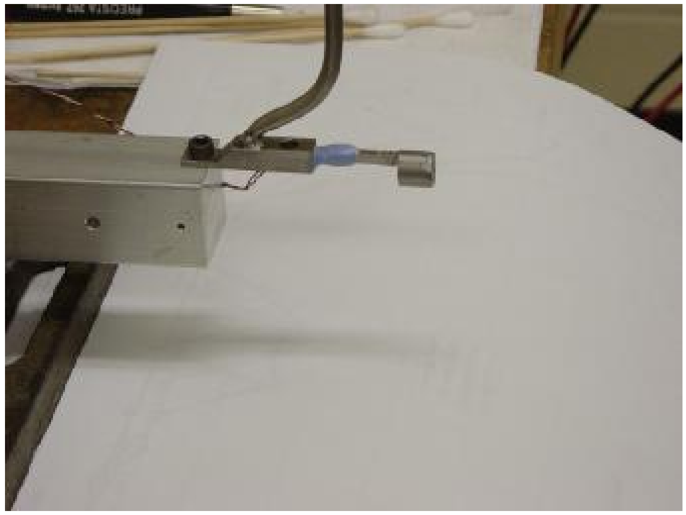

Figure 3-1. A Drag Type Direct Surge Probe Ready for Installation with the Drag Body, the Bending Element with covered Strain Gauges, the Support, and a Tube for Signal Wires

of compressor, but if all of the issues are considered, can result in an effective, reliable, and practical means of connecting the surge probe to an external bridge amplifier and signal monitoring circuit.

- Design and select the surge controller, which can be an adaptation of a current technology controller that is able to monitor the compressor's suction and discharge pressures and temperatures, and the compressor speed and flow signals. The surge probe signals that the controller must monitor are two voltages from bridge type amplifiers that are usually in the range of ±10 to ±5 volts and represent the total axial and tangential strains. Strain gauge outputs contain high frequency information and internal compressor flow can change rapidly; however, a controller sample rate of 150 to 200 Hz should be adequate to follow the pre-surge flow changes and control the compressor. Independent of the other data, the direct surge controller should be able to sample, filter, or short average, and process and compare the two strain signals rapidly. A view of the surge detection display for the prototype direct surge controller is shown in Figure 3-2.

- Refinement or tuning of the control algorithm is required to control a compressor's recycle valve from the direct surge probe signals. This is the development step currently being conducted as part of the direct surge control research. If the difference between the two strain signals is taken as shown in Figure 2-8, then small positive values (5 micro-strain) or a zero crossing could be used to trigger initial action (recycle valve opening) and a stable negative value (-5 to -10 micro-strain) could be taken as the minimum recycle, most efficient, operating point when surge control is needed. This option should be applicable to essentially all modern compressors. Other algorithms are possible and could be considered in the future.

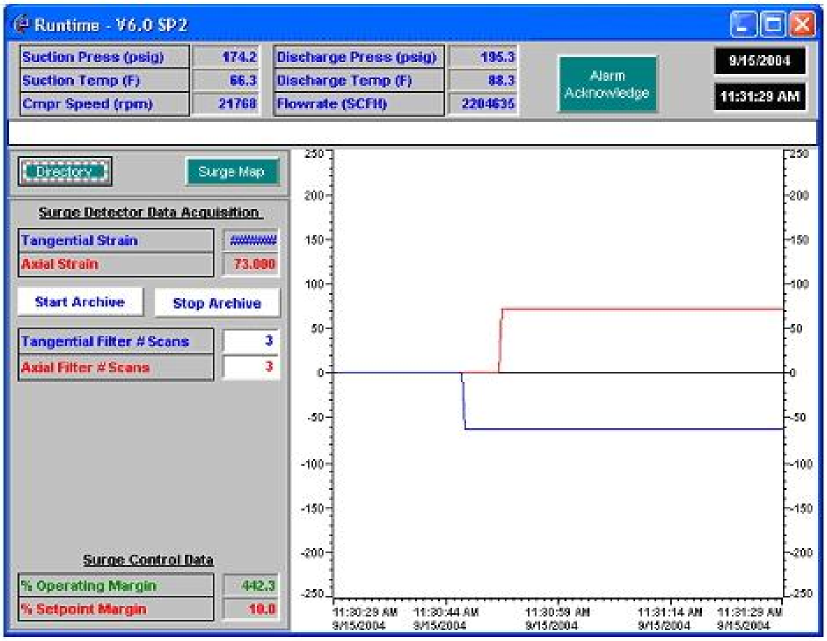

Figure 3-2. Surge Detection Display from Prototype Direct Surge Controller

4. CONCLUSIONS

The following conclusions are drawn from the test results to date.

- Surge is a potentially damaging flow instability that limits the low-flow operation of centrifugal compressors and is usually avoided by recycling flow to maintain an arbitrary minimum flow above a surge margin. This can be wasteful when more flow is recycled than necessary and is costly in terms of energy and fuel when the compressor operation is maintained above the near-surge conditions at which the compressor can safely operate without recycled flow.

- Early GMRC research identified a flow re-circulation along the outer wall of a centrifugal compressor inlet as a precursor for surge and a potential control signal. In addition, it was found that most other signals, including vibration and pulsation, are NOT reliable indicators of approaching surge. A drag type probe was found to be practical and reliable for measuring these local re-circulating flows.

- Test results have shown that for the impeller inlet face flow measurements to be sensitive to the near surge re-circulating flow, the impeller must be of a modern 3D design with blades at the inlet face of the impeller.

- Flow changes along the outer wall of a centrifugal compressor inlet do produce re-circulating flows as surge approaches, which causes the axial flow-induced strain on a properly located drag probe to decrease, potentially pass through a local peak, and then continue to decrease as surge is approached. The re-circulation also causes an increase in the tangential strain particularly as the compressor approaches close to surge. These changes in strain are somewhat affected by the details of the surge detection probe location and the compressor geometry but are at least similar for all of the modern compressors tested.

- A step-by-step design procedure for direct surge control probes and controllers has been defined by this research and is enumerated in the previous part of this report. Although a probe design will have to be completed for each new compressor model and pressure or flow range, the results will be similar for compressors of a given type and size. Controllers, once fully developed, will be applicable to all direct surge installations.

- The control algorithm developed is based on comparing the difference between the decreasing axial strain and the increasing tangential strain. This algorithm works well for all the data collected in modern compressors to date, emphasizes the changes caused by the re-circulating flow, and is less sensitive to details of the strain changes than most other algorithms.

5. REFERENCES

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2. Mizuki, S. and Oosawa, Y., "Unsteady Flow Within Centrifugal Compressor Channels Under Rotating Stall and Surge," *Transactions of the ASME*, Vol. 114, April 1992, pp. 312-320.