NASA/TM—2005-213553 AIAA–2005–0849

Closed Loop Active Flow Separation Detection and Control in a Multistage Compressor

Michelle M. Bright, Dennis E. Culley, and Edward P. Braunscheidel
Glenn Research Center, Cleveland, Ohio

Gerard E. Welch
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

May 2005

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2005-213553 AIAA–2005–0849

Closed Loop Active Flow Separation Detection and Control in a Multistage Compressor

Michelle M. Bright, Dennis E. Culley, and Edward P. Braunscheidel
Glenn Research Center, Cleveland, Ohio

Gerard E. Welch
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

Prepared for the
43rd Aerospace Sciences Meeting and Exhibit
sponsored by the American Institute of Aeronautics and Astronautics
Reno, Nevada, January 10–13, 2005

National Aeronautics and
Space Administration

Glenn Research Center

May 2005

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Closed Loop Active Flow Separation Detection and Control in a Multistage Compressor

Michelle M. Bright, Dennis E. Culley, and Edward J. Braunscheidel
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Gerard E. Welch
U.S. Army Research Laboratory
Glenn Research Center
Cleveland, Ohio 44135

Active closed loop flow control was successfully demonstrated on a full annulus of stator vanes in a low speed axial compressor. Two independent methods of detecting separated flow conditions on the vane suction surface were developed. The first technique detects changes in static pressure along the vane suction surface, while the second method monitors variation in the potential field of the downstream rotor. Both methods may feasibly be used in future engines employing embedded flow control technology. In response to the detection of separated conditions, injection along the suction surface of each vane was used. Injected mass flow on the suction surface of stator vanes is known to reduce separation and the resulting limitation on static pressure rise due to lowered diffusion in the vane passage. A control algorithm was developed which provided a proportional response of the injected mass flow to the degree of separation, thereby minimizing the performance penalty on the compressor system.

Introduction

The long-term objective of our research is to develop and demonstrate flow control methods that use air injection in high-speed compressors for control of flow separation within stators. Separation control may enable improved performance by increasing the range of incidence angles over which total pressure loss is acceptable, and by increasing the loading level at which an acceptable level of loss occurs. This, in turn, may improve operability through increased stator aerodynamic loading, which can lead to reduced engine weight and parts count through lower solidity.

Fluidic flow control is an emerging research technology that can be applied to aircraft engine components to manage diffusing boundary layers. In a paper by Ball [1], fluidic control was demonstrated in an offset S-type diffuser. Wadia [2] and Kerrebrock [3] patented self-aspirating compressor concepts to significantly increase pressure ratio in a turbomachinery fan. Bons and River [4] have also investigated the use of unsteady pulsed vortex generator jets to control low-pressure turbine boundary layer separation. In their work, they attached flow along a turbine vane using a combination of low and high frequency unsteadiness, imparted by the vortex generator. These results were corroborated by Culley [5] in our four-stage Low Speed Axial (LSAC) Compressor facility on two individual stator vanes. A paper by Kirtley [6] investigates a full annulus flow-controlled compressor stator ring to reduce vane count by 30 percent and increase stage efficiency by 2.1 points. Building on previous success with the Culley [5] experiments using two stator vanes, we investigated a full-annulus experiment for active closed-loop flow control for this paper.

The metric used to determine the effectiveness of stator suction surface injection was the measurement of pressure loss coefficient which is directly related to separation induced blockage in the vane passage. To this end, reductions in normalized loss coefficient on the order of 25 percent were documented previously in a two-vane experiment (see Culley et al). The significance of this result indicates that active flow separation control within the compressor stator row can increase turbomachinery performance by reducing component weight in two ways. First, by maintaining current stage loading with a reduced blade count (lowered solidity), or by increasing stage loading with the same blade count (eliminating stages). The component weight has a direct impact on fuel efficiency and emissions.

This paper will show results of the full annulus experiment using steady injection along 42 of the 52 stator vanes in the first stage of a four stage compressor rig. The paper will show results of steady injection on performance for this full complement of stators, as it is used in the flow control logic. It will also concentrate on the development of stator vane separation control methods using a low speed compressor, specifically, active control of injection when the blade separates. This paper will describe an algorithm for use in autonomous control of separation via injection. Previous success was attained using only two actively controlled stator vanes in the LSAC compressor rig. Active separation control requires a method of sensing the onset of separation. Results are presented that demonstrate separation sensing using time-averaged vane surface pressure measurements and discusses a second method using time-resolved casing static pressure measurements in a full-annulus experiment.

Experimental Description

The design of the full annulus experiment was painstakingly developed over a year long period. The current experiment was performed in a large, low speed research compressor and was developed as an extension of previous work performed in a limited sector of that machine. The prior effort is fully described in Culley [5]. While the sector work was demonstrated to be an efficient method for examining a very large parameter space, the full annulus test provides a test bed for evaluation of closed loop control in a realistic compressor configuration. Outlined below is a description of the research compressor, the flow control configuration, the flow delivery system, and the active control scheme.

The current experiment is performed in a large, low speed research compressor and is developed as an extension of previous work which was performed in a limited sector of that same machine. The prior effort is fully described in Culley [5]. While the sector work was demonstrated to be an efficient method of quickly examining a very large parameter space at a local level, it was inconclusive regarding the response of the machine. The full annulus experiment is designed to answer some of those questions.

A more detailed description of the research compressor, the flow control vanes, the flow delivery system, and the separation detection and control scheme follows in the next four sections, respectively.

Research Compressor

The NASA Glenn Low Speed Axial Compressor (LSAC) facility is used for this study. Air enters the facility through a filtered roof vent, is conditioned for temperature and turbulence, and then passes through a calibrated bellmouth and into the research compressor. Airflow exiting the compressor is controlled by a throttle valve, close-coupled to the collector, and discharged into either an atmospheric or altitude exhaust system. A 1500-hp variable speed motor drives the compressor rotor.

The compressor consists of an inlet guide vane and four identical stages designed for accurate low-speed simulation of the rear stages of a high-speed core compressor. A long entrance duct is used to develop thick endwall boundary layers typical of an embedded stage. The first stage is rigged with 42 flow control stator vanes used for control. The flow path has an outer diameter of 1.219 m and a hub-tip radius ratio of 0.80. All stators have inner shrouds with a single labyrinth seal-tooth in the shrouded stator cavity. The nominal rotor tip and stator seal clearances are 1.4 and 0.6 percent of span, respectively. Rotor tip speed is 61 m/sec and nominal axial velocity is on the order of 25 m/sec. The increased size and low speed of this facility enables intrastage surveys of the flow field thus making possible an increased understanding of the complex flow phenomena within multi-stage axial compressors. A complete description of the LSAC facility is given by Wasserbauer [7].

The blading used for the current tests is based on the Rotor B/Stator B blading designed by General Electric for the NASA Energy Efficient Engine program. Details of the original designs are reported by Wisler [8]. The stators are designed by applying modified 65-series thickness distributions to modified circular-arc meanlines. The NASA stators are slightly modified from the GE design to accommodate a difference in hub-tip radius ratio between the GE and NASA low speed compressor facilities. The NASA stator features a solidity of 1.38, an aspect ratio of 1.32, a stagger angle of 42° and a camber of 40.5°. The stator chord is 9.4 cm. Stators are sealed at both the hub and tip junctions with the flow path.

The flow over the LSAC stator vanes is not prone to strong separation prior to compressor stall. Therefore, the vanes are installed at a stagger angle increase of approximately 4° from nominal to induce early flow separation. Surface pressure measurements acquired from a pair of instrumented stator vanes indicate that at this re-stagger the vanes are not separated under open-throttle conditions but suffer a severe separation at lower flow coefficients.

Flow Control Vane Configuration

Previous flow control experiments have been performed in the LSAC stage 3 window using rapid prototyped flow control vanes. As part of this previous effort the use of laser sintering fabrication techniques were extensively explored because of its cost effectiveness in developing complex internal flow geometry. This test article fabrication process has been extended in the full annulus configuration to cover 42 of the 52 vanes in stage 1.

Structural considerations preclude the use of flow control vanes in all 52 vane positions. Examination of the structural design of the stator vane row reveals that 10 of the vanes are used to transmit loads between the inner and outer hub rings. For structural integrity these specific vane locations require the use of fiberglass vanes. The installation of these vanes is illustrated in figure 1(e).

The flow control vanes are identical to those used in Culley [5] and are designed to produce a sheet of near tangential injection along the suction surface at 35 percent chord. The extent of coverage is approximately 10 to 90 percent of span. To fabricate these vanes cost effectively a laser sintered rapid prototyping process is used.

Shown in figure 1(a) is an image of the flow control vane. Injection air enters the tip end trunion and passes into an internal cavity where it is blown into the vane passage through a set of six slots on the vane surface. The cavity, and the features within, produces a flow distribution from the slots that is within 10 percent of the average. A second version of the vane is shown in figure 1(b). It is identical to the first except that it includes pressure sensing ports at 5, 70, 75, and 80 percent of chord on the suction surface. A fifth tube is installed in the cavity to sense the internal pressure driving the injection jet. In figure 1(c) a photograph of the finished vane is shown along with the hardware which serves to both mechanically secure the blade to the hub ring and attach the air supply tubing.

There are 52 vanes in the stator annulus. Of these, 42 are flow control vanes and the remaining ten are solid fiberglass. The 10 fiberglass vanes are required to support the load of the hub and foot rings. Two of the 42 flow control vanes are instrumented with the additional pressure sensing ports. Shown in figure 1(e) is half of the assembled stator annulus prior to being mounted in the compressor rig.

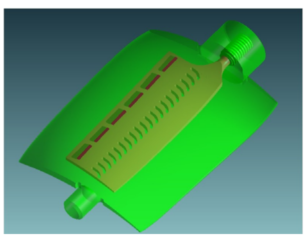

Figure 1(a).—Flow-controlled blades.

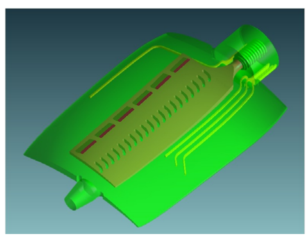

Figure 1(b).—Showing four static taps at mid-span on suction-side.

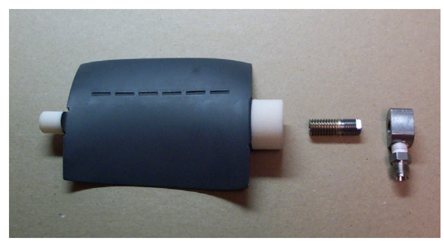

Figure 1(c).—New compact design for air feed line. Hookup.

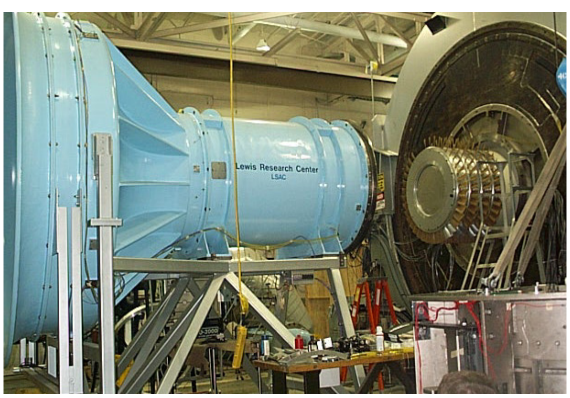

Figure 1(d).—Low-speed axial compressor.

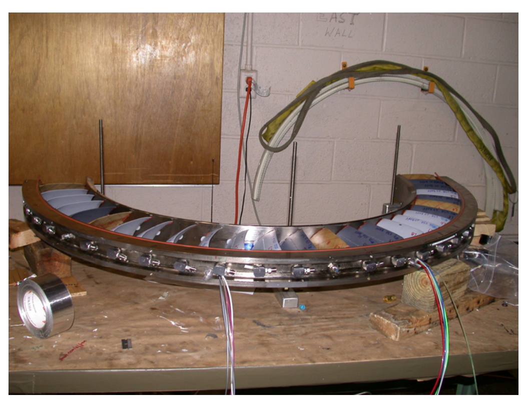

Figure 1(e).—Half of stator 1 blade row with F blades installed.

The Flow Delivery System

Figure 2 is a schematic representation of the flow control system including the flow control vanes. Injection air is supplied by a filtered shop air line available in the facility. A remotely-operated control valve enables the precise metering of the injected massflow rate to the vanes. The flow rate is measured with a massflow meter to an accuracy of ±1 percent full scale. The meter is isolated by two large accumulators at its output which feed 21 flow control vanes each. The accumulator filters out rapid fluctuations in the flow, which will interfere with the accuracy of the flow meter. The accumulator also serves as a stable pressure source for the downstream components of the flow system.

The flow delivery system is designed to meter and supply injection air to the flow control vanes in the stator annulus. Air passes through a mass flow meter where the bulk injection flow rate is measured. This quantity is controlled using a motorized v-notch ball valve mounted at the base of the rig. Immediately following the control valve the flow is split and enters two large pressure vessels, each with a volume of 6.8 liters, located on either side of the rig. The east and west accumulators reduce the velocity of the incoming flow by a factor of 10 so that it can be evenly distributed to the vanes.

A uniform distribution of flow relies on symmetry in the distribution system. Extreme care has been taken to ensure that all components in the flow path are identical. The limiting factor, however, is the pressure drop across the 15 foot length of 0.25 inch outside diameter tubing which connects each flow control vane to the accumulator. To monitor the flow distribution system each accumulator is instrumented for pressure and temperature. Two of the flow control vanes are also equipped with static pressure sensing in the internal cavity of the vane to verify flow balance and correlate the calibration values with the experimental injection rates.

In figure 3 the sensing and control parameters used in open and closed loop tests are shown. At the tip end of each flow control vane, a high frequency piezo-electric pressure transducer is used to measure time-resolved delivery system dynamics. In some configurations a 1 mm diameter tube is inserted into the internal flow control vane cavity to measure the time averaged total pressure, $\overline{P}_{jet}$, of the injected flow. Another high frequency piezo-electric pressure signal, p'_c, originates in the casing over the stator vane to track fluid disturbances related to vane separation dynamics. The injected massflow is both a measured value, $\dot{m}_{jet}$, as well as a controlled parameter, $\dot{m}_{cjet}$. All of these signals are tied to a high bandwidth data acquisition and control system.

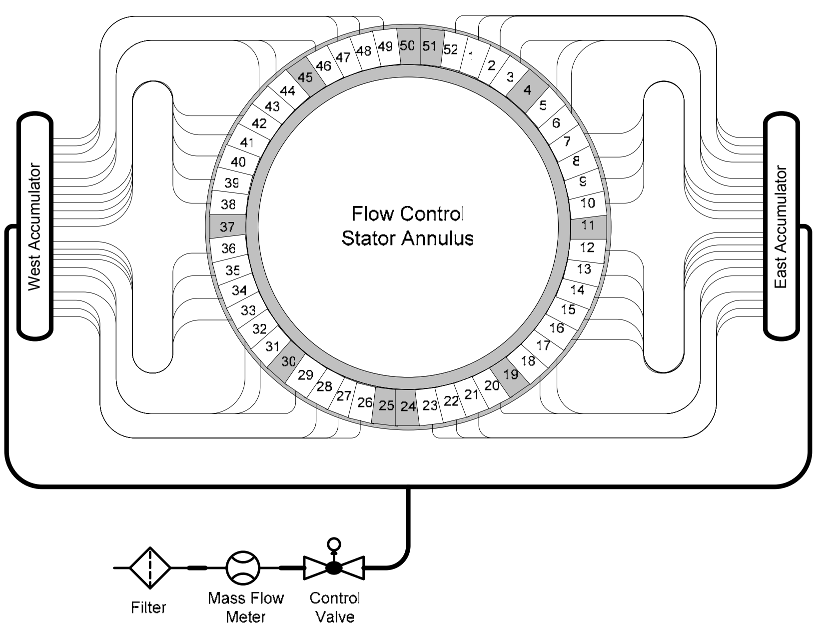

Figure 2.—Flow delivery system.

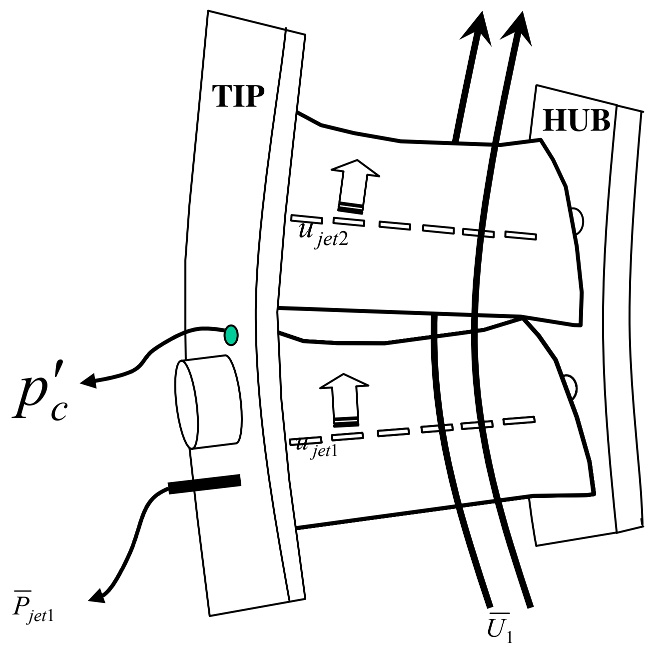

Figure 3.—Schematic of the flow control actuation system.

Separation Detection and Control Scheme

This effort explored two methods capable of active sensing and closed loop control of vane surface separation. Closed loop separation control is desirable because it commands injection only when necessary, thus minimizing the thermodynamic cycle penalty associated with the increased compressor bleed, which is the source of air needed for injection. In an installed compressor, separation is an effect of off-design loading caused by throttle transients, distortion, and increased clearances due to deterioration. In the LSAC, loading changes are induced by closing the rig throttle valve. Our closed loop control architecture is therefore based on forcing the onset of vane suction surface separation using changes in the throttle position, and reducing the separation using massflow input to the vane. The signals required to implement control are the massflow input, $\dot{m}_{jet}$, the massflow commanded, $\dot{m}_{cjet}$, and the pressure, p_{delta}, measured across the vane.

Implementation of a closed-loop control scheme requires a method of detecting separation. Two separation detection schemes were developed. Both these schemes were developed for a two-vane experiment, and are now described for the full annulus test. The first scheme employs a flow control vane with suction surface static pressure taps located at 70 and 85 percent chord and 56 percent span. The pressure rise between these two locations provides the controller with information on the pressure gradient over the rear of the vane. This type of detection scheme is achieved using static pressure measurements along the vane surface. An example of this method is shown in figure 4.

The second separation detection scheme investigated uses a pressure transducer located in the casing next to the vane suction surface at 85 percent chord (fig. 4). This scheme was developed because it requires access to only a casing static pressure. This should therefore be less costly to implement in an engine than the scheme described above which requires an instrumented airfoil. This detection scheme is based on a time-series analysis of the casing static pressure and works as follows. The wake shed from the vane causes an unsteady loading of the downstream rotor. The first Fourier harmonic of the rotor blade passing frequency is a measure of the wake-induced pressure variation generated by the rotor. Since vane surface separation causes increased wake strength, a separation can be detected from the casing static pressure signal by monitoring the power in the first harmonic.

In a control strategy for the vane, the power of the first Fourier harmonic of the pressure signal could be used to determine when to switch injection on or off. When the power of the first Fourier harmonic rises above a threshold level, the control computer automatically opens a valve to begin injection. The injected massflow from the vane surface is then varied proportionally to the casing signal strength. This is shown in figure 5.

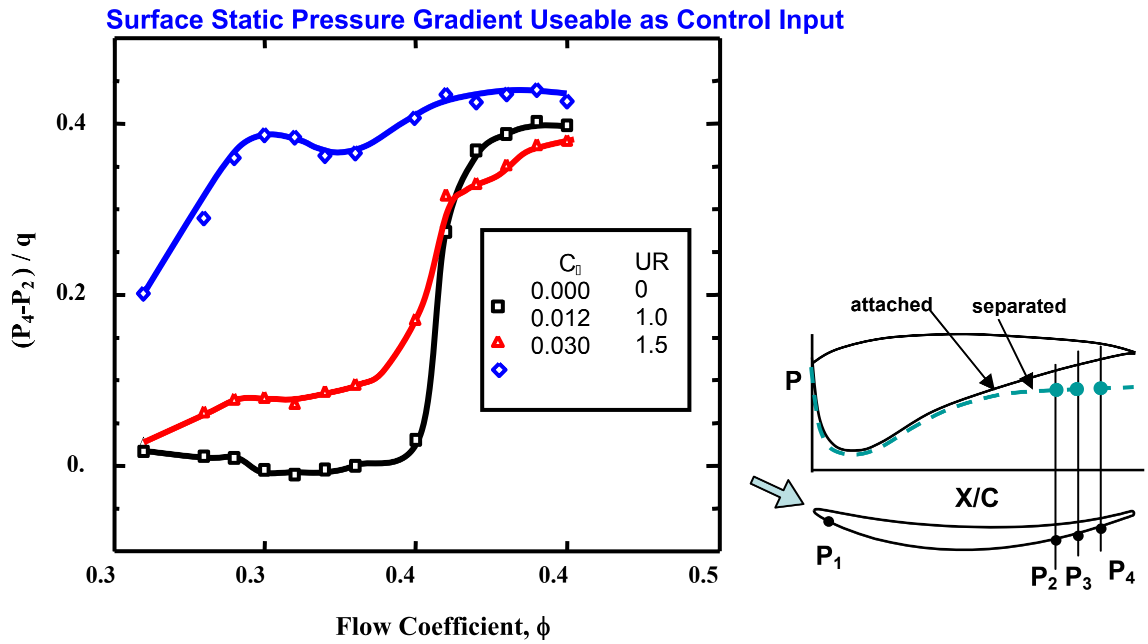

Figure 4.—Sensing separation from blade surface pressures.

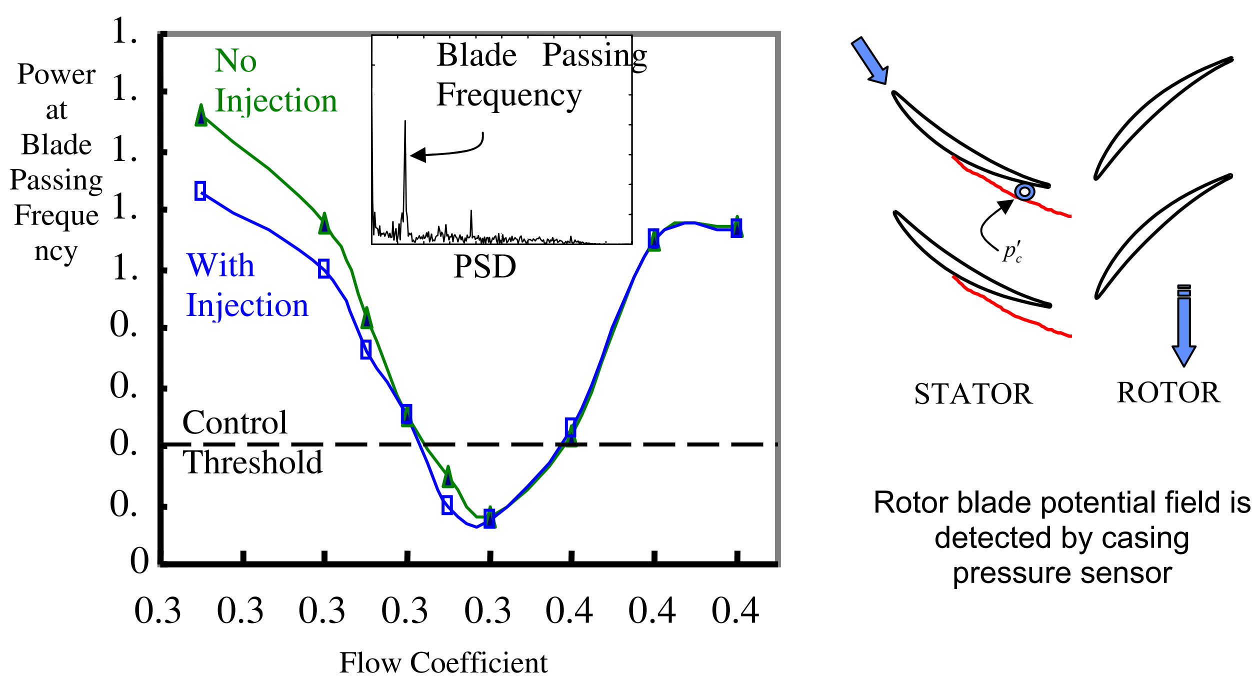

Figure 5.—Method of measuring rotor blade potential field to sense separation.

Results and Discussion

Two sets of experiments were performed in the full annulus configuration. The first set of experiments documented the use of steady injection along all 42 stator vanes at varying levels of injection to establish performance benefits at stage 1 and subsequent effect to the downstream rotors. This information was used to establish the control strategy for the second set of experiments to investigate closed-loop control.

In the steady injection experiments, results were obtained from the pressure measurements across the vane. As the mass flow through the compressor was varied, a measure of deltap across the vane was recorded. In the first experiment, the stator vane angle was set to –4° stagger to induce separation. Figure 6 is a result from this experiment where deltap across the vane is plotted versus mass flow through the compressor.

In the plot, an injected mass flow of 0.084 kg/sec of steady injection is used. It is shown that the deltap across the vane (which corresponds to the flow being attached) is high until the mass flow through the compressor reached 0.36. The deltap decreases sharply until the flow through the compressor reaches 0.32. The blade is then shown to be fully separated since the deltap is near zero. When no injection is present, the flow begins to separate when the compressor mass flow (phi) is 0.39 and is fully separated by the time the compressor is at a flow condition of 0.35. This plot provides two pieces of information for the control. With no injection present, the compressor stator vane separates around 0.39 and is fully separated at a flow condition of 0.35. When injection is present, the compressor stator vane separates at a flow condition of 0.36. Without injection the vane separates at a flow condition of 0.39. The control needs to apply injected air up to a level of 0.084 kg/sec to reattach the flow and determine when to turn off the injection when the flow is not separated.

The control scheme as shown in the MATLAB/simulink diagram of figure 7 shows the simple configuration used for the full annulus experiment. The control was implemented in real-time on a Dspace PC-based control computer using Real-Time Interface software/hardware. As the flow through the compressor is varied by changing the throttle, the flow across the vane (deltap) is monitored, as well as the level of injection supplied to each vane. For the experiment only a single vane is monitored for separation, however, all 42 vanes are supplied with the same control input, and the same level of injected flow. As the vane separates, injection air is supplied proportionally to the stators to delay separation. This was accomplished using 0.084 kg/sec of injection air. The controller tracked when the vanes were separated and supplied a proportional amount of injected air. When the compressor mass flow setting was throttled open, the controller sensed that the stator was no longer separated and turned off injection. The controller tracked either the injected flow condition or the no-injected flow condition as appropriate.

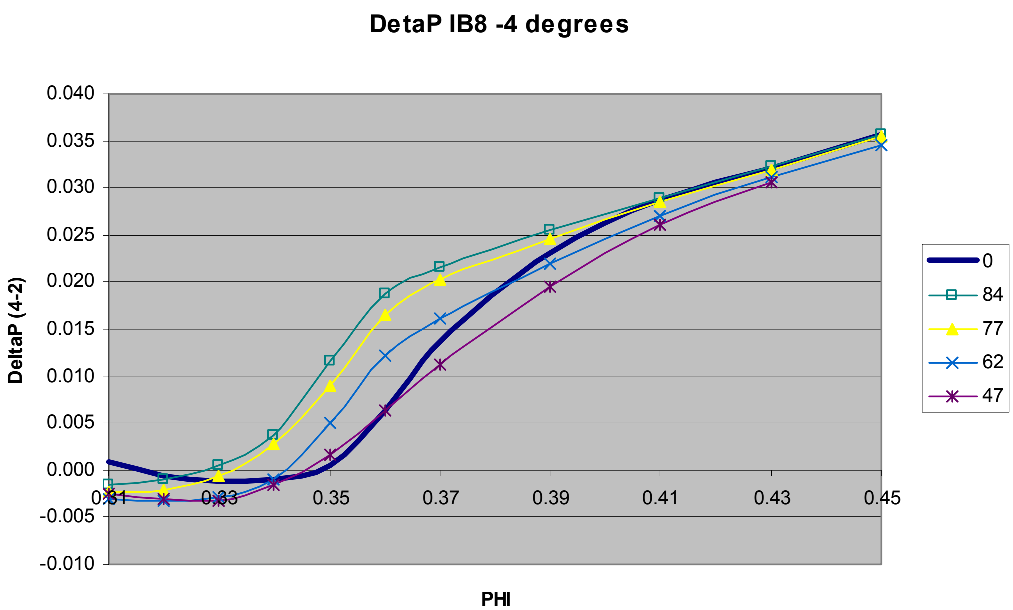

Figure 6.—DeltaP across the stator vane.

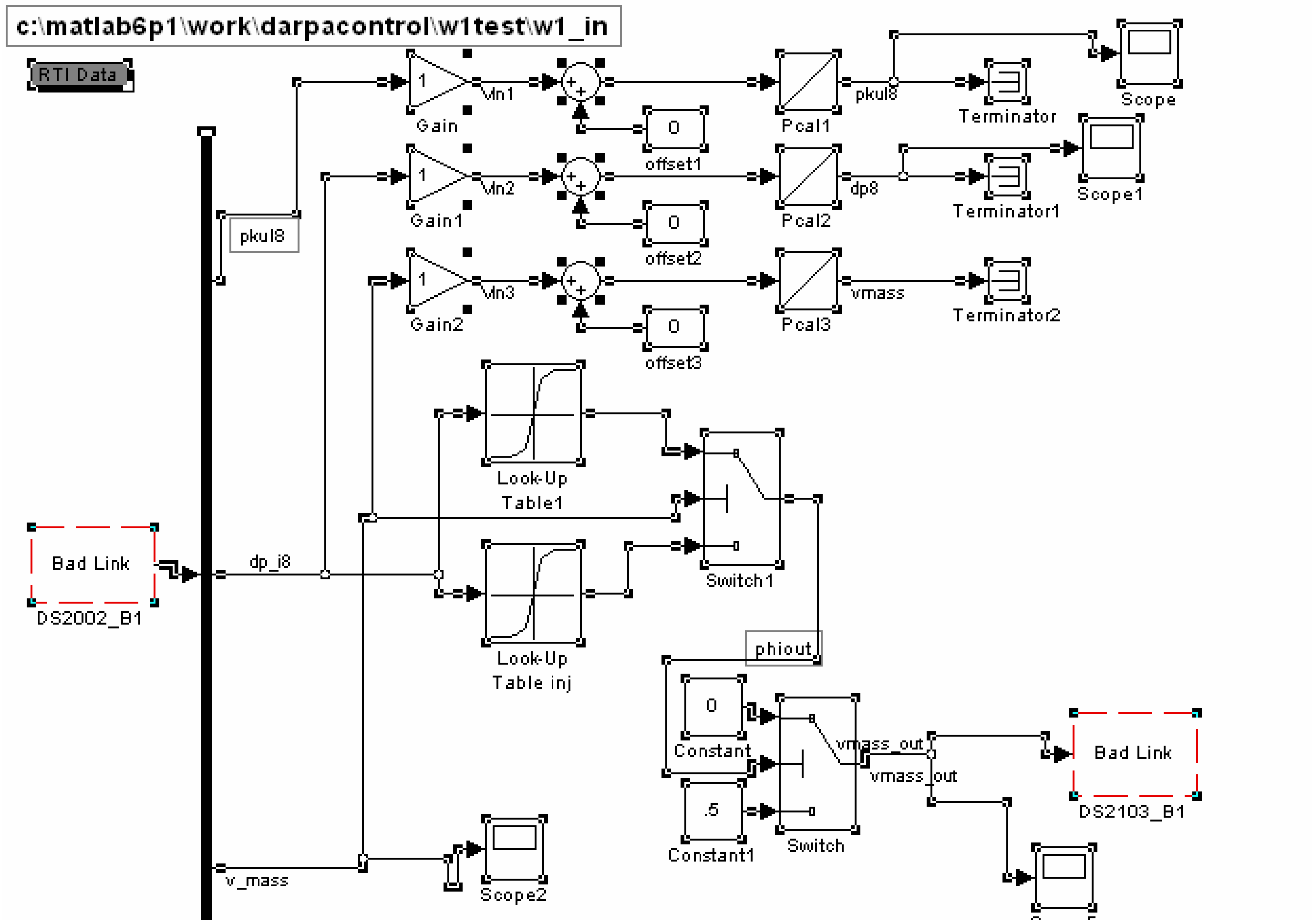

Figure 7.—Control architecture for DSpace controller.

Another experiment performed for this test was the validation of a kulite in the casing method to sense separation. Figure 8 shows a plot of the PSD of the kulite as the throttle condition is varied from 0.45 to 0.34 with and without injection. A single transducer records the pressure fluctuations present at the casing near the stator vane. A PSD of the kulite signal is calculated and the amplitude at blade passage frequency of this signal is monitored. When the PSD amplitude is below 0.55, the flow is attached to the vane. As the peak of the PSD begins to rise, this indicates separation has occurred. Using steady injection, the PSD amplitude is lowered and the flow is attached. Figure 8 shows that as the throttle condition is varied below a phi = 0.39, the vane begins to separate for the no injection case. When 0.084 kg/s of injection is used, the PSD remains below 0.55 until a phi = 0.36 is reached. Then the flow begins to separate. This PSD method indicates a separation at the same time that the deltap across the vane indicates separation. Thus, a single sensor in the casing in a full annulus experiment can be used to detect and control separation when the PSD is calculated to monitor blade passage frequency harmonics.

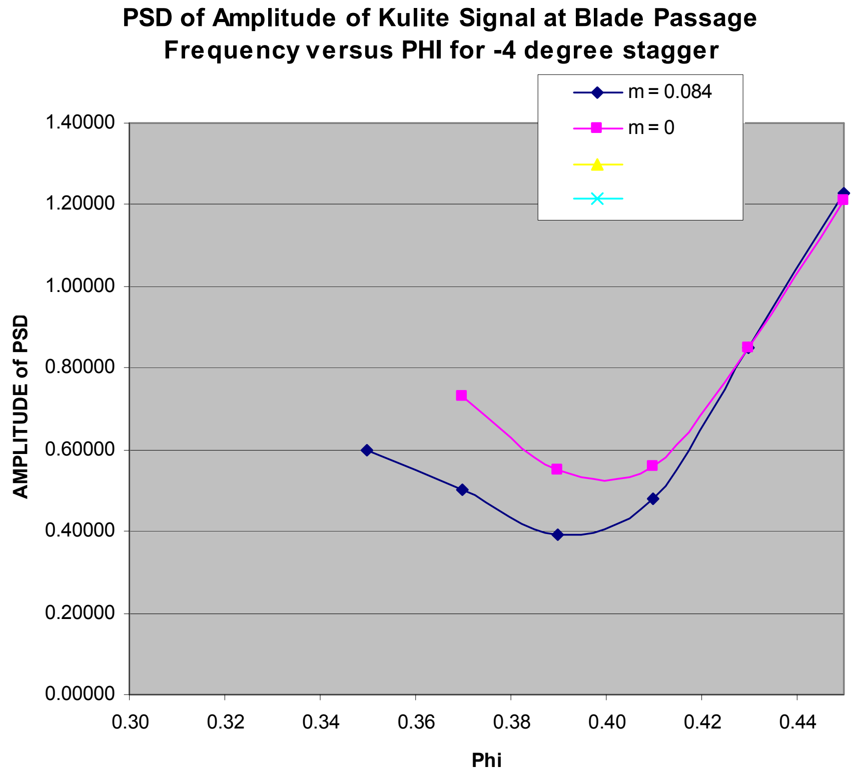

Figure 8.—PSD of kulite signal as throttle is varied.

Conclusion

Control of stator vane suction surface separation was demonstrated in a low speed multistage compressor using steady injection on the suction surface of 42 vanes. Steady injection experiments were used to determine the appropriate level of injection to reattach flow along the stator vane surface. This information was supplied to the control scheme for successful real-time closed loop control for the first compressor stage.

Spectral analysis of the casing static pressure measured near the vane-endwall junction was found to provide a reliable indicator of the degree of vane separation. Another method using the change in static pressure along the vane surface of a single vane was used as control input to a real-time closed loop control experiment. The design of a feedback control system that modulated vane injection to control separation was successfully demonstrated. Results indicated that these two methods were viable for separation detection and control. Future experiments, however, show that locating the actuator close to or embedded in the stator vane it self will provide a more adequate means of control.

References

[1] Ball, W.H., 1983, “Experimental Investigation of the Effects of Wall Suction and Blowing on the Performance of Highly Offset Diffusers,” AIAA Paper 83–1169.
[2] Wadia, Aspi R., and Mielke, Mark J., “Self Bleeding Rotor,” US Patent 5,480,284, filed 1993, issued 1996.
[3] Kerrebrock, J.L., Reignen, D.P, Ziminsky, W.S., and Smilg, L.M., 1997, “Aspirated Compressors,” ASME Paper 97-GT-525.
[4] Bons, J.P., Sondergaard, R. and Rivir, R.B., “The Fluid Dynamics of LPT Blade Separation Control Using Pulsed Jets,” ASME Paper 2001-GT-0190.
[5] Culley, D., Bright, M., Strazisar, A., “Active Flow Separation Control of a Stator Vane Using Embedded Injection in a Multistage Compressor Experiment,” ASME J. of Turbomachinery, Vol. 126, p. 24, 2004.
[6] Kirtley, K.R., Graziosi, P., Wood, P., Beacher, B., and H.-W. Shin, 2004, “Design and Test of an Ultra-Low Solidity Flow-Controlled Compressor Stator,” ASME Paper 2004-GT-53012.
[7] Wasserbauer, C.A., Weaver, H.F., and Senyitko, R.G., 1995, “NASA Low Speed Compressor for Fundamental Research,” NASA TM4635.
[8] Wisler, D.C., 1977, “Core Compressor Exit Stage Study: Volume I – Blade Design,” NASA CR135391.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
May 2005

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Closed Loop Active Flow Separation Detection and Control in a Multistage Compressor

5. FUNDING NUMBERS
WBS–22–714–70–54

6. AUTHOR(S)
Michelle M. Bright, Dennis E. Culley, Edward P. Braunscheidel, and Gerard E. Welch

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135 – 3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E – 14993

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546 – 0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM — 2005-213553
AIAA–2005–0849

11. SUPPLEMENTARY NOTES
Prepared for the 43rd Aerospace Sciences Meeting and Exhibit sponsored by the American Institute of Aeronautics and Astronautics, Reno, Nevada, January 10–13, 2005. Michelle M. Bright, Dennis E. Culley, and Edward P. Braunscheidel, NASA Glenn Research Center; and Gerard E. Welch, U.S. Army Research Laboratory, NASA Glenn Research Center. Responsible person, Michelle M. Bright, organization code RIC, 216–433–2304.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories: 02, 07, and 09
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Active closed loop flow control was successfully demonstrated on a full annulus of stator vanes in a low speed axial compressor. Two independent methods of detecting separated flow conditions on the vane suction surface were developed. The first technique detects changes in static pressure along the vane suction surface, while the second method monitors variation in the potential field of the downstream rotor. Both methods may feasibly be used in future engines employing embedded flow control technology. In response to the detection of separated conditions, injection along the suction surface of each vane was used. Injected mass flow on the suction surface of stator vanes is known to reduce separation and the resulting limitation on static pressure rise due to lowered diffusion in the vane passage. A control algorithm was developed which provided a proportional response of the injected mass flow to the degree of separation, thereby minimizing the performance penalty on the compressor system.

14. SUBJECT TERMS
Active flow control; Compressor; Turbomachinery

15. NUMBER OF PAGES
15

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	