

## New Concepts for Active Control of Rotating Stall and Surge

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**Abstract**— Flow instabilities in transonic compressors include rotating stall and surge. Air Injection control has been demonstrated to be an effective strategy for actively suppressing rotating stall and surge. In industrial applications such as aero-engines, the implementation of air injection control schemes is constrained by factors such as the “cost” in terms of efficiency lost and availability of high pressure air, and the size and weight of the actuation system. Air will typically be re-circulated from a downstream compressor stage. The challenge, then, is to create control schemes that achieve acceptable performance with less air and fewer actuators. In this paper, new control concepts to address these implementation challenges in active control of rotating stall and surge are presented. The single-sided injection control scheme was used to reduce the net mass injected, notch-based control strategy was used to provide a framework for implementing nonlinear controllers to high speed compressors, and control laws that incorporate the discrete nature of the actuators are used to reduce the number of actuators. Results from experimental validation with data from high speed compressors are presented.

### I. INTRODUCTION

Rotating stall and surge are aerodynamic instabilities that limit the operating range, performance, and reliability of gas turbine engines. Rotating stall is a two- or three-dimensional non-axisymmetric phenomenon whereby portions of the flow with velocity deficit (known as stall cells) travel around the compressor annulus at 30% to 70% of the rotor speed. Surge is a large amplitude one-dimensional (axisymmetric) flow oscillation in the compressor. Rotating stall must be avoided in axial flow compressors because it can lead to severe unsteady loading on the compressor blades which can in turn lead to excessive blade vibration, a large drop in the pressure rise delivered by the compressor, a dramatic drop in the compressor efficiency which may cause the burner to overheat, and possibly surge. Surge overstresses the compressor blades, and can blow out the flame in the combustor (this is known as engine flame-out) leading to

engine shut-down, and damage. If the compressor for a jet engine that does not surge (low B parameter) settles into a stable rotating stall, the engine may not recover from this condition unless it is shut-down and re-started.

The traditional approach for avoiding rotating stall is to operate the compressor away from the stall point. This approach requires operating the engine with a stall margin or stability margin so that any transients or disturbances will not drive the system to rotating stall. However, operating the compressor with a stall margin will limit the range and performance of the compressor since it will be operating at a lower pressure rise, possibly with lower efficiency. This is wasteful, and a more modern approach for increasing the useful operating range and thus maximizing the pressure rise and efficiency from the compressor is by active control.

In 1989, Epstein et al. [1] proposed the use of active feedback control techniques to extend the compressor operating range by delaying the onset of rotating stall and surge. This involves the integration of sensors and actuators into the compression system so that the unsteady flow perturbations, which are the precursors of rotating stall and surge, can be measured and subsequently stabilized by applying appropriate feedback control.

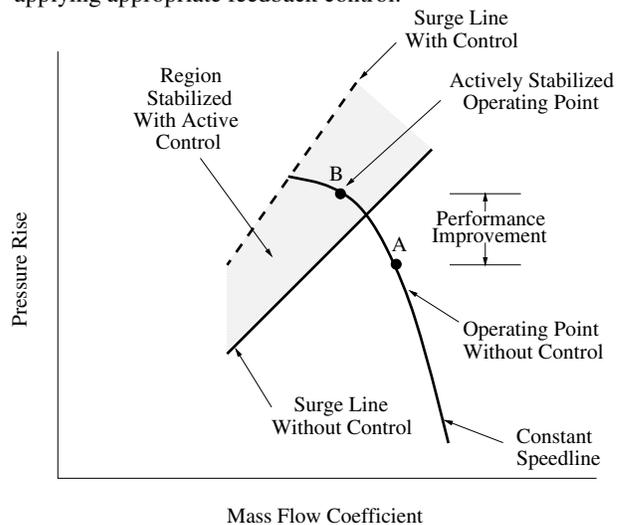


Figure 1: Closed loop compressor characteristic showing operation range extension with active feedback control

Figure 1 shows how the compressor surge line can be moved with active feedback control. Without feedback control, the compressor is operated at point A to maintain a safety margin from the surge line. With active feedback

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control, the surge line is moved to the left such that the compressor can be operated at point B. Thus with active feedback control, the compressor can be operated at higher performance levels. Over the years, the validity of this concept has been demonstrated on several research compressors [2 – 12].

In industrial applications such as aeroengines, implementation of air injection control schemes is constrained by factors such as the cost in terms of efficiency lost and availability of high pressure air, as well as the size and weight of the actuation scheme. Air will typically be re-circulated from a downstream compressor stage. The challenge, then, is to implement control strategies that achieve acceptable performance with less air and fewer actuators. Validated control concepts to address these implementation challenges in active control of rotating stall and surge are presented in this paper. In the sections that follow, the experimental setup used for the control experiments are described, the control concepts for reducing the actuation requirements for rotating stall and surge are presented, and results from control experiments on a high speed compressor used to validate these concepts are presented.

## II. EXPERIMENTAL SETUP

The control experiments reported in this paper were conducted at the NASA John H. Glenn Research Center Single-Stage Axial Compressor Test Facility [13]. This is an open circuit facility for testing advanced compressor stages such as NASA Stages 35, 37, and 38 which are representative of the inlet, middle, and rear stages for an eight-stage 20:1 pressure ratio core compressor. A 2.2 Megawatt DC drive motor drives the compressor in the test section. Air at atmospheric pressure passes through a calibrated thin-plate orifice and upstream plenum which contains a straightening screen to ensure uniform flow in the test section.

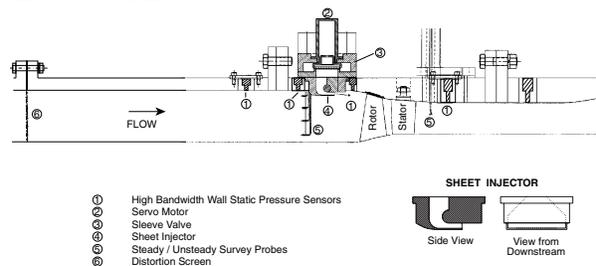


Figure 2: Meridional cross-sectional view of casing configuration for NASA Stage 35.

At the test section, the air goes from the upstream duct through the compressor stage where the pressure is increased to the downstream duct, through the throttle and then exhausted to the atmosphere. The throttle is a sleeve-type valve which regulates the amount of air going through

the compressor by adjusting the exit area. The test section was instrumented with jet actuators, steady sensors, and unsteady sensors. A meridional cross-sectional view of the test section showing the axial locations of the actuators, steady sensors, and unsteady sensors is shown in Figure 2.

## III. CONTROL CONCEPTS

The new control concepts presented in this paper include single-sided injection strategy, notch-based control strategy, and actuation reduction control strategy.

### A. Single-Sided Control Strategy

Previous work on high speed compressors [12, 14] have demonstrated that steady injection of high pressure air can increase the pressure rise and extend the operating range of axial flow compressors. However, steady injection is not the most efficient way of using the control power provided by high pressure air. Forced response measurements have demonstrated that unsteady air injection provides an effective lever on the pre-stall dynamics of high speed compressors. This led to the use of active feedback control to obtain even further range extension. The current state of the art requires air to be injected about a mean level so that the time average mean injection remains constant. This unsteady injection strategy is referred to as double-sided injection because air is injected at levels above and below the mean. A more effective actuation strategy that combines the advantages of steady and unsteady injection is single-sided injection.

With the single-sided injection strategy, air is only injected above a certain baseline level (usually zero). In the double-sided case, in contrast, air is injected above and below the mean available blowing. The main difference between single-sided injection and double-sided injection is that for single-sided injection, the control input can move only in one direction, whereas for double-sided injection, the control input can move in both directions about a constant mean. Thus the mean level of injection is constant with double-sided injection while the mean level of injection with single-sided injection depends on the amplitude of the circumferentially non-uniform component. Using the single-sided injection scheme for control makes use of the effects of steady injection and unsteady injection to control rotating stall. Since single-sided injection results in an unsteadiness-dependent mean blowing, the time-averaged blowing will increase with unsteadiness. Thus two effects, which have both been demonstrated to extend the stable operating range, are introduced: increasing the stable operating range by increasing the mean level of injection, and stabilization of unstable modes by unsteady injection. Control laws which use single-sided blowing should take advantage of both of these effects, and a cumulative improvement will be possible with less overall

blowing. The single-sided injection scheme is illustrated in Figure 3 using a first harmonic constant gain feedback control Law.

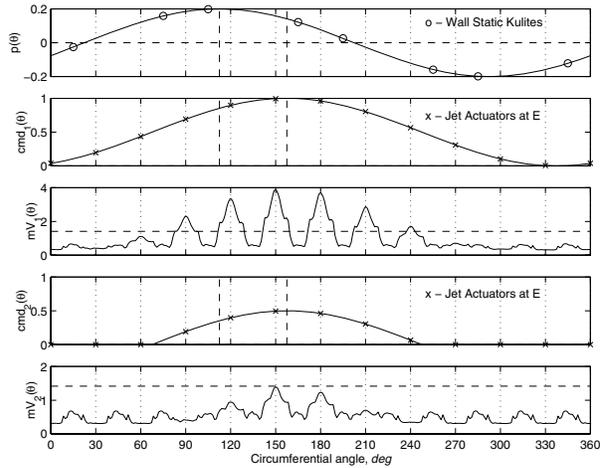


Figure 3: Constant gain rotating stall control using double-sided and single-sided injection schemes.

The constant gain feedback control law is given by:

$$\tilde{u}_n = -Z_n \cdot \tilde{\psi}_n \quad (1)$$

where  $\tilde{\psi}_n$  is the  $n^{\text{th}}$  spatial Fourier coefficient (SFC) of the static pressure perturbations measured at the sensor location,  $\tilde{u}_n$  is the  $n^{\text{th}}$  harmonic SFC of the actuation (injection) wave, which is introduced as an  $n^{\text{th}}$  harmonic sinusoidal wave, and  $Z_n$  is a constant complex gain. The amplitude of the control gain,  $|Z_n|$ , is the scaling between the measured pressure perturbations SFC and commanded harmonic injection SFC, and is fixed for all frequencies. The phase angle of  $Z_n$ , is the spatial offset between the input and output waves and is also fixed for all frequencies. In Figure 3, the first plot shows the first harmonic of the measured pressure perturbation wave. The second plot shows the twelve actuator commands, which have been scaled and offset in the circumferential direction by the control gain, for double-sided injection. The third plot shows the corresponding momentum flux profile injected at the tip by the sheet injector. Since the injected mass flow varies linearly with the valve position, the injected mass flow is also sinusoidal about a mean value of 3.6% injection level. The magnitude of the momentum flux with the valves half open is indicated by a dashed line. The momentum is normalized by the upstream duct freestream value. The momentum flux is less than the baseline value of 1.0 for the injectors with low mass flows because the sheet injectors stick out into the compressor inlet duct. The fourth plot shows the twelve actuator commands for single-sided injection with the valves nominally-off, and the bottom plot shows the corresponding momentum flux profile injected at the tip by the sheet injector. The potential for reducing the mass flow for effective control with a single-sided actuation

scheme can be easily seen from the analytical expression for the mean injection level of a first harmonic constant gain control law with single-sided actuation which is given by:

$$\bar{\gamma}_{cg1s} = \gamma_0 + \frac{A}{\pi} \quad (2)$$

where  $\gamma_0$  is the baseline injection level or corresponding mean injection level for double-sided injection, and  $A$  is the first harmonic amplitude. At the nominally-off position, the mean injection level reduces to  $A/\pi$ . Thus, control laws which use single-sided unsteady blowing can take advantage of the steady and unsteady effects of air injection vis-a-vis stable operating range extension, and a cumulative improvement will be possible with less overall blowing.

### B. Notch-Based Control Strategy

Single-sided injection provides us with an actuation strategy for reducing the amount of mass required to extend the stable operating range for axial compressors. But single-sided injection is inherently a nonlinear actuation strategy because of the changes in time-average blowing. This implies that nonlinear models will be needed to design control laws that maximize the effects of single-sided injection.

The existence of multiple modes in high speed compressors has been demonstrated analytically [15, 16], and experimentally [12]. These modes are classified as incompressible and compressible. Tryfonidis et al. [17, 18] studied the stall inception data for various compressors and found that stall-inception could be initiated by either the incompressible modes or compressible modes. The incompressible modes are the Moore-Greitzer rotating stall modes that have been identified in low speed machines. The rotation rates of these incompressible rotating stall modes depend on the compressor rotation frequency. The compressible modes are the acoustic modes due to compressibility. The rotation rates of these compressible modes are governed by the speed of sound. The acoustic modes do not play any role in the stall inception of low speed machines because of the wide separation in rotation rates between the incompressible and compressible modes. In high speed machines, the rotation rates of the incompressible modes and compressible (or acoustic) modes are of the same order. Thus, there is the potential for spillover in high speed machines due to the closeness in rotation frequencies between the incompressible and compressible modes. For example, control laws designed based on nonlinear models for low speed machines will be able to stabilize the incompressible rotating stall modes. However, if these nonlinear control laws are implemented in high speed compressors, they could excite and destabilize the acoustic modes while stabilizing the incompressible rotating stall modes. Such a destabilizing effect was observed by Weigl et al. [12] on NASA Stage 35 using a

first harmonic constant gain feedback controller. Even though the stall inception in NASA Stage 35 was initiated by the incompressible rotating stall modes, a constant gain control law was unable to stabilize the transonic compressor at 100% speed. The first harmonic constant gain controller was shown to damp the rotating stall mode while destabilizing some acoustic modes.

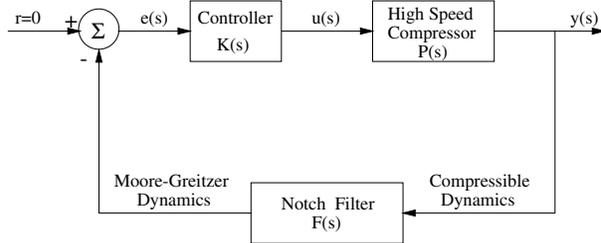


Figure 4: Block diagram of notch-based control concept for implementing nonlinear control laws.

The proposed control concept for alleviating this spillover effect is to append an incompressible state estimator to the nonlinear control laws designed based on the low speed models. The rationale for this control concept is to make sure that the acoustic modes which do not initiate the stall inception in NASA Stage 35 are not excited. By estimating the incompressible states from the high speed compressor measurements, only the incompressible dynamics are fed back as illustrated in Figure 4. Refer to [19] for details of the design of the incompressible state estimators from the compressible dynamics.

### C. Reducing the Number of Actuators

The spatial harmonic approach is the current state-of-the-art for rotating stall and surge control. The implicit assumption with the spatial harmonic approach is that the actuators can generate a continuous wave profile. However, the discrete nature of the actuators is demonstrated in Figure 3 which plots the momentum flux injected at the tip by the sheet injectors for a first harmonic constant gain feedback controller. A continuous actuation wave profile can be generated with an infinite number of actuators, thus the effectiveness of harmonic controllers will increase with the number of actuators. The range extension obtained with the spatial harmonic controllers using twelve actuators demonstrate that twelve actuators is sufficient since it can generate up to the fifth harmonic. In an industrial setting such as an aircraft engine application, a more plausible active control strategy to be implemented will require about three or four big actuators instead of twelve. For such cases, spatial harmonic control laws will break down. A more effective control strategy will be one that accounts for the discrete nature of the four actuators. To account for the discrete nature of the actuators, the effect of each actuator on each harmonic of the pre-stall perturbations will have to

be identified.

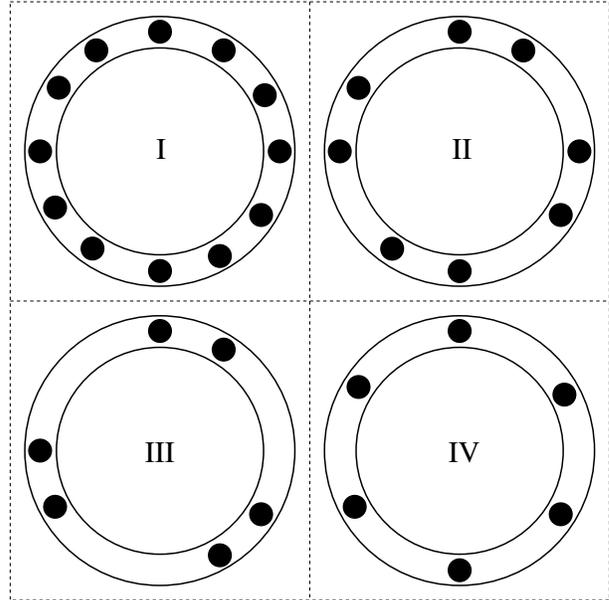


Figure 5: Configurations for twelve, eight, and six actuators.

Figure 5 shows four actuation configurations that were experimentally investigated in this research. These configurations were selected based on parametric actuation studies involving various configurations for twelve, eight, and six actuators. Actuation configuration I is the baseline configuration of twelve actuators equally spaced around the compressor annulus; actuation configuration II which consists of four ganged actuators (i.e., four groups of two actuators), represents a plausible configuration for four big actuators; actuation configuration III which consists of three ganged actuators (i.e., three groups of two actuators), represents a plausible configuration for three big actuators; and actuation configuration IV is the configuration for implementing the spatial harmonic control with six actuators equally spaced around the compressor annulus. Two criteria were used to quantify the performance of each actuation configuration: the RMS of actuator activity when the closed loop system is subjected to a unit intensity white noise, and the RMS of total control effort required to stabilize the compressor. The RMS of total control effort is defined as the RMS of control activity in excess of the baseline multiplied by the number of actuators.

The control concept for reducing the number of actuators required for effective control of compressor instabilities consists of implementing control laws that incorporate the discrete nature of the actuators. The general multi-input multi-output (MIMO) system for these configurations of actuators is represented by:

$$\tilde{y}(s) = G(s) \cdot \tilde{u}(s) \quad (3)$$

where the output vector  $\tilde{y}$  represents the spatial Fourier

coefficients (SFCs) of the static pressure perturbations and the input vector  $\tilde{u}$  represents the command from each of the actuators. The transfer function matrix,  $G(s)$ , is made up of elements  $G_{ij}(s)$  which represent the transfer function between the  $j^{\text{th}}$  actuator input command and the  $i^{\text{th}}$  harmonic of the pre-stall perturbations. The state-space representation of the MIMO system can be identified from the transfer functions  $G_{ij}(s)$  using standard system identification tools such as MATLAB or FORSE (Frequency dependent Observability Range Space Extension). By identifying the elements  $G_{ij}(s)$  i.e., the effect of each actuator on the different spatial harmonics, the discrete nature of the actuators can be incorporated into the system model. An  $H_{\infty}$  robust control law can then be designed for the MIMO system.

#### IV. RESULTS AND DISCUSSION

The control concept of appending incompressible state estimators to control laws that stabilize only the Moore-Greitzer rotating stall mode was implemented on NASA Stage 35 with a radially distorted inlet flow. Since the radial distortion screen is circumferentially uniform, the flow profiles are also circumferentially uniform and the harmonics of circumferential pressure perturbations are decoupled as is the case with a uniform inlet flow. The first harmonic empirical transfer function estimate (ETFE) at 85% speed and a mass flow rate of 14.79 kg/s (near stall) is shown in Figure 6.

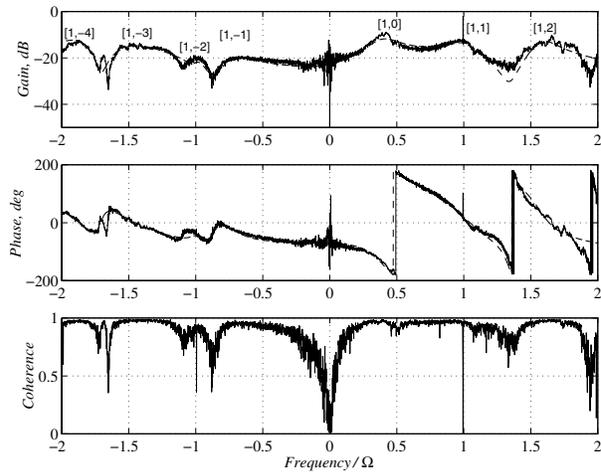


Figure 6: First Harmonic ETFE at 85% speed and 14.79 kg/s.

At this speed, the tip relative Mach number for this compressor is 1.25. The measured transfer function shows the existence of a lightly damped low-frequency rotating stall (or Moore-Greitzer) mode as well as compressible (or acoustic) modes. The single-input single output (SISO) transfer function representation for each spatial harmonic can be considered to be the sum of the lightly damped

incompressible rotating stall or Moore-Greitzer modes and the compressible or acoustic modes.

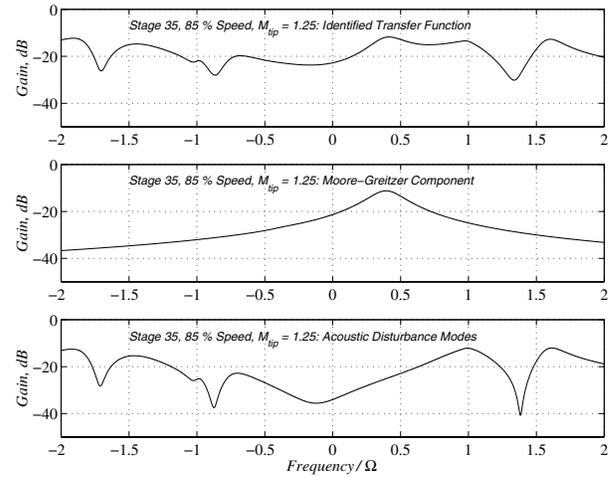


Figure 7: Identified first harmonic transfer function at 85% speed and 14.79 kg/s.

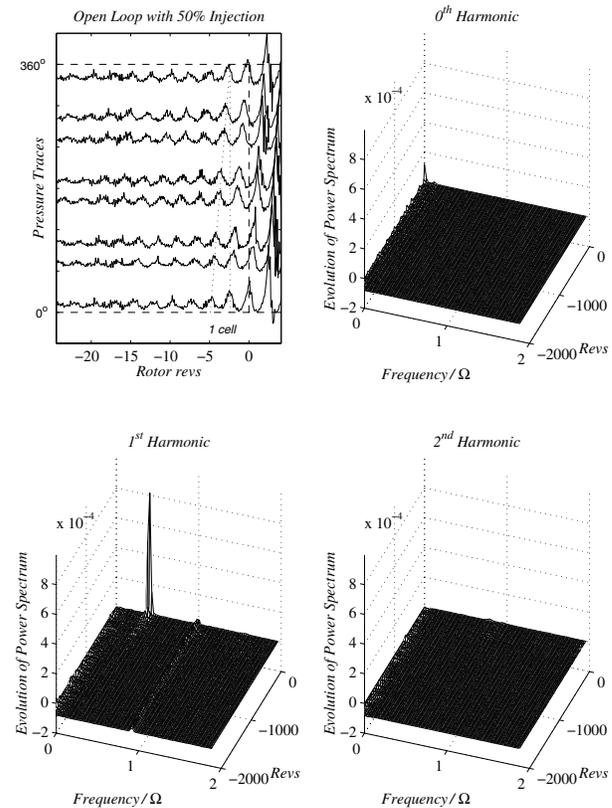


Figure 8: 85% speed throttle ramp for NASA Stage 35 with inlet radial distortion and steady mean injection.

Thus, the pre-stall dynamics for the high speed compressor can be modeled by the following transfer function:

$$y(s) = [G_{MG}(s) + G_{DIS}(s)] \cdot u(s) \quad (4)$$

where  $u(t)$  is the input to the compression system consisting of a process disturbance signal and a measurement disturbance signal. The identified first harmonic transfer function, obtained by fitting polynomials to the measurements in Figure 6, and the corresponding Moore-Greitzer and acoustic disturbance components obtained using the formulation given in equation (4) is shown in Figure 7. Figure 8 shows the open loop stall inception data at 85% speed with mean blowing. The static pressure traces and the accompanying spectrograms show that the mode driving the compressor into stall is the first harmonic incompressible Moore-Greitzer mode traveling around the annulus at about 40% of the rotor speed. The first harmonic compressible  $[1, 1]$  mode traveling around the annulus at about 80% of the rotor speed is also present but does not grow.

To demonstrate the effectiveness of the control concept of appending incompressible state estimators to controllers that stabilize only the incompressible Moore-Greitzer modes, a root locus analysis was performed using estimated dynamics of the unstable transonic compressor dynamics. Since the compressor was driven to instability by the  $[1, 0]$  rotating stall mode, the unstable dynamics of the plant was estimated from the identified system dynamics in Figure 6 by making the  $[1, 0]$  mode unstable. The root locus analysis for the unstable plant using a first harmonic constant gain control law is shown in Figure 9.

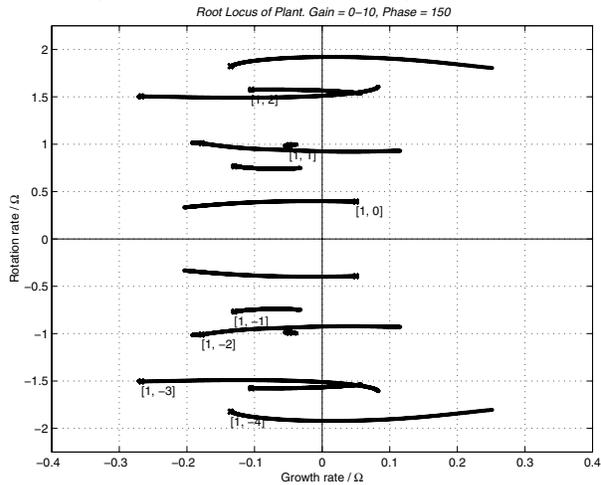


Figure 9: Root locus without incompressible state estimator.

The results show that the first harmonic constant gain controller stabilizes the incompressible Moore-Greitzer rotating stall  $[1, 0]$  mode that was shown to be driving the transonic compressor into stall. However, the first harmonic constant gain controller destabilizes the acoustic modes  $[1, 2]$ ,  $[1, -2]$ ,  $[1, -3]$ , and  $[1, -4]$ . As shown by the root locus analysis in Figure 10, the incompressible Moore-Greitzer mode is stabilized and the acoustic modes are not destabilized when an optimal minimax filter is appended to

the first harmonic constant gain controller.

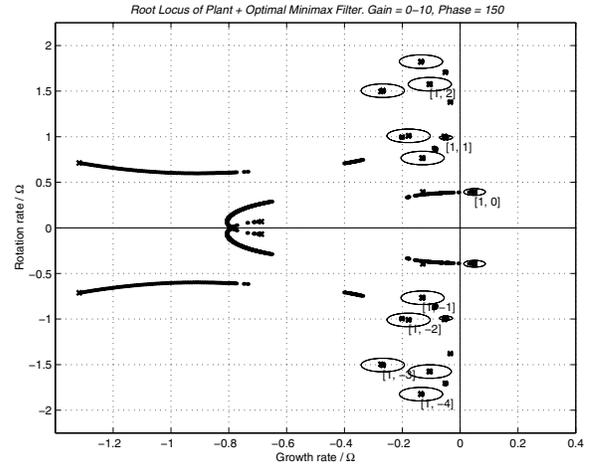


Figure 10: 85% speed root locus analysis for first harmonic constant gain controller with optimal minimax estimator.

Examination of the transfer functions showed that the optimal minimax filter inverts the acoustic disturbance such that the resulting open loop system is the incompressible Moore-Greitzer mode that can be stabilized with the first harmonic constant gain controller.

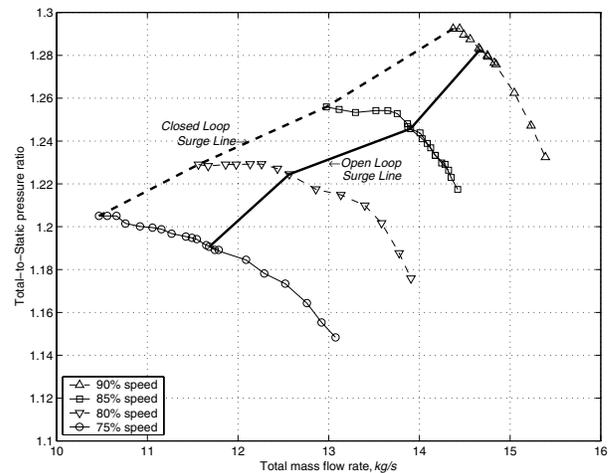


Figure 11: Closed loop speedlines from first harmonic notch-based control of NASA Stage 35 with inlet radial distortion.

To test this control concept on NASA Stage 35, the first harmonic constant gain control law without any estimators appended to it was first used to stabilize the compressor at 85% speed. No range extension was obtained. This was because some acoustic modes were excited and destabilized by the first harmonic constant gain controller. However, when the first harmonic constant gain controller was appended with the optimal minimax filter, the stalling mass flow rate was decreased to 12.98 kg/s, a reduction of 20.3% from the stall point of 16.28 kg/s for the transonic compressor operating at 85% speed with inlet radial distortion. This corresponds to an additional range

extension of 9% above the reduction obtained with steady mean injection. To evaluate the robustness of this control concept to changes in compressor speed, the optimal minimax filter designed using the identified system dynamics at 85% speed was used in conjunction with the constant gain controller to stabilize the transonic compressor at 75%, 80%, 85%, and 90% speeds. The closed loop speedlines are shown in Figure 11. These speedlines show that the operating range extension increases as the compressor speed is decreased from 90% to 75%, indicating that this control concept is robust to changes in compressor speed.

Control experiments for different actuator configurations with fewer actuators were implemented on NASA Stage 35 with a circumferentially distorted inlet flow. Coupling between harmonics due to circumferential distortion was observed to have a positive effect from a control standpoint, in that a constant gain controller was able to stabilize the compressor. This was in contrast to the cases with uniform flow and radial distortion, where the harmonics were uncoupled and an incompressible state estimator had to be appended with the constant gain controller before the compressor could be stabilized. Using the experimentally tuned optimal gain, the first harmonic constant gain controller was used to evaluate the effectiveness of the different actuator configurations in Figure 5. Pressure traces and first harmonic power spectrum showed that open loop stall inception was initiated by the incompressible rotating stall or Moore-Greitzer [1, 0] mode, at  $0.4\Omega$ , since it was the first mode to go unstable. The first harmonic compressible [1, 1] mode was present but does not grow. A constant gain controller was experimentally tuned to damp the [1, 0] mode. The optimal gain for the constant gain controller was found to be  $Z_1 = 2e^{\pi}$ . The first harmonic power spectrum showed that the [1, 0] mode was completely damped out. The pressure traces and second harmonic power spectrum showed that the second harmonic incompressible rotating stall [2, 0] mode was the first to go unstable. The unsteady stall inception data for the first harmonic constant gain controller with actuation configuration II showed a similar behavior to the closed loop stall inception with actuation configuration I. The only difference was that the closed loop stall inception with actuation configuration II was soft (small amplitude perturbations) whereas the closed loop stall inception with actuation configuration I was hard (large amplitude perturbations). The pressure traces and first harmonic spectra for configurations III and IV showed that the incompressible rotating stall [1, 0] mode was not completely damped out for both configurations which consisted of six actuators and the closed loop stall inception for these configurations were still initiated by the [1, 0] mode at  $0.4\Omega$ . Since the actuators were not saturated,

higher gains may have been able to completely damp out this mode. These results imply that the gains will have to be increased as the number of actuators is reduced to completely damp out the unstable modes. This observation is consistent with the trend from parametric simulation results which showed that higher gains were required to stabilize the compressor for the actuators in actuation configurations III and IV than from the actuators in actuation configurations I and II. The reductions in stalling mass flow rate obtained with first harmonic constant gain feedback control using the experimentally tuned optimal gain of  $Z_1 = 2e^{\pi}$  for the four actuation configurations are shown in Figure 12. The actuator valves were nominally half-opened, air was being supplied at 100 psig, and the sheet injectors were oriented at  $-15^\circ$  yaw. Without feedback, the stalling mass flow rate was reduced by 8.7% compared to the case with no injection, which stalled at 15.70 kg/s with circumferential distortion. First harmonic constant gain control reduced the stalling mass flow rate by 18.4%, 14.4%, 13.2%, and 13.5% for actuation configurations I, II, III, and IV respectively.

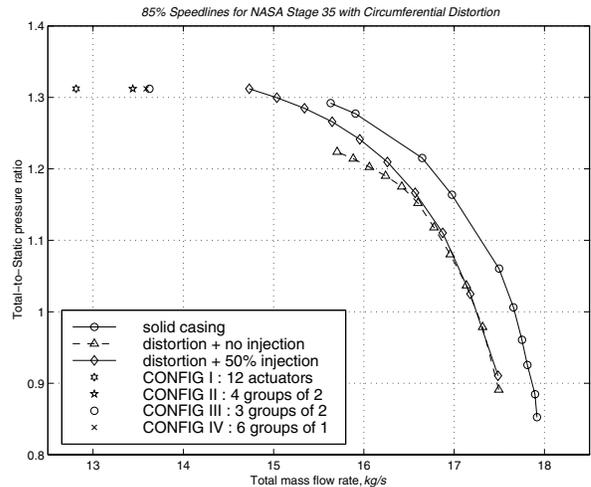


Figure 12: 85% closed loop speedlines for NASA Stage 35 with inlet circumferential distortion for actuation configurations in Figure 5 using an optimally tuned first harmonic constant gain controller.

## V. CONCLUSION

New control concepts for reducing the air injection requirements (net mass flow and number of actuators) for effective stabilization of compressor instabilities were developed, and validated experimentally. Single-sided actuation was proposed as the actuation strategy for reducing the net mass flow requirements. This was motivated by the fact that single-sided unsteady blowing has two avenues for extending the stable operating range - stabilization of unstable modes, and increased levels of time-averaged blowing as unsteadiness increases.

Even though the stall inception of the single-stage transonic compressor used for this research was initiated by the incompressible rotating stall modes, a constant gain feedback control law (which has been demonstrated in low speed compressors to be able to stabilize these incompressible modes) was unable to stabilize the transonic compressor. This observed behavior is due to the spillover effects of the acoustic modes. To alleviate the spillover effects of the acoustic modes, a control concept was proposed whereby incompressible state estimators were appended to control laws that only consider the incompressible rotating stall modes. In this way, only the incompressible dynamics were measured and fed back. This control concept was validated experimentally on a transonic compressor operating at 85% speed with an inlet radial distortion. By implementing a simple first harmonic constant gain controller appended with a robust  $H_{\infty}$  estimator, the stable operating range of the transonic compressor was extended by 9% beyond the stall point at mean injection. The results from the control experiments showed that this control concept maintains the robustness of  $H_{\infty}$  and is robust to changes in the compressor speed. This control approach provides a framework for the conceptualization and implementation of nonlinear control laws such as the sliding mode control law.

From the results presented in this paper, it can be concluded that:

- 1) For high speed compressors whose stall inception is initiated by the incompressible rotating stall modes but cannot be stabilized by control laws that consider only the incompressible rotating stall modes due to spillover effects from the acoustic modes, an effective concept for alleviating the spillover effects from the acoustic modes is to append incompressible state estimators to the control laws.
- 2) A major step in reducing the levels of blowing required to stabilize rotating stall and surge in axial flow compressors is to implement control laws using single-sided injection with the valves nominally-off.
- 3) It is feasible to extend the stable operating range of the transonic compressor with three big actuators which have the same control authority as six of the actuators used in this research. It is assumed that no additional actuator delays would be incurred by implementing these actuation configurations.

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