

**ACTIVE CONTROL OF
INTEGRATED INLET / COMPRESSION SYSTEMS:
INITIAL RESULTS**

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ABSTRACT

Substantial reductions in aircraft size are possible if shorter, more aggressive, serpentine inlet ducts are used for low-observability constrained propulsion installations. To obtain this benefit, both inlet separation and compressor stall dynamics must be controlled. In this paper the integrated control of this coupled inlet/compression system is considered. Initial results are shown using separation point actuation to control both separation and stall dynamics. Calculations show that separation can be substantially reduced with approximately 1.2% core flow, based on scaling previous results. Simulation results using a medium fidelity model show that proportional control of distortion has little effect on stall behavior.

1 INTRODUCTION

The inlet to an aircraft propulsion system must supply flow to the compressor with minimal pressure loss, distortion, or unsteadiness; the former reduces the overall system performance, while the latter effects can result in stall or surge of the compressor. For many military applications, the inlet design is also constrained by low observability requirements. To reduce the radar signature from the compressor face, a serpentine inlet is typically used to block line-of-sight. Similar buried propulsion system installations have also been considered for some configurations of the commercial blended wing body design. While the inlet length that is required to avoid separation and its associated losses may not be a significant design driver for some vehicles, in other configurations (such as uninhabited air vehicles), the inlet may drive the size of the overall vehicle. Therefore,

technologies such as flow control that can enable more aggressive inlets can have significant overall system benefit.

In order to make the vehicle smaller through the use of such technologies, constraints imposed by the compressor dynamics may also need to be considered. Instability of these dynamics is typically avoided by introducing a stall margin; i.e. by operating the compressor at less than the peak pressure rise to allow for inlet distortion, transients, and wear. This requires the use of additional stages to obtain the desired net pressure rise from the compression system, resulting in a heavier engine.

Current aircraft designs typically consider the compressor and inlet as separate sub-systems, where the connection between them is given as a pressure recovery and distortion specification [1, 2] that must be met at the Aerodynamic Interface Plane (AIP). This approach is not entirely adequate for today's aircraft, due to the coupling between the inlet and compressor performance and stability, and it is inadequate if advanced inlet or compressor control approaches are to be designed.

The compressor behavior must be considered together with the inlet for several reasons. First, reducing the amount of stall margin required for stability enables the compressor to operate at higher pressure rise and potentially improved efficiency, allowing reduced engine size and fuel requirements that may be essential in obtaining the reduced vehicle size associated with a shorter inlet. Second, any technology that enables a shorter inlet to retain the same pressure recovery as a current technology inlet would be inadequate if it does not also address distortion and unsteadiness. However, such technology might be very complementary with compressor stability control; rather than requiring the shorter inlet to provide the same distortion as the original inlet, allow a higher distortion and compensate

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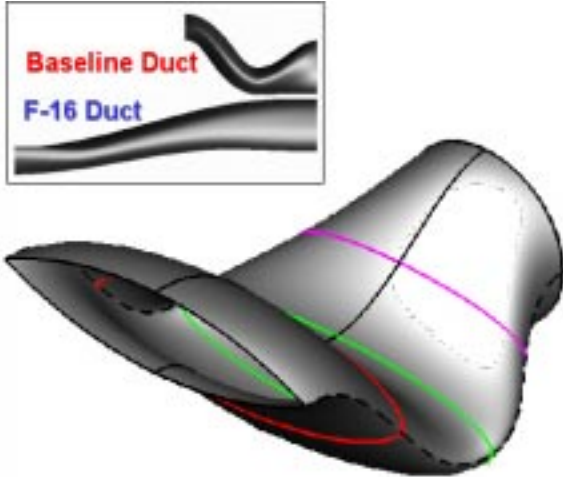


Figure 1: Aggressive L/D 2.5 serpentine inlet duct, and comparison with current F-16 inlet. This compact design involves two turns, diffusion, and change in shape.

by controlling the compressor. Third, the physical systems are coupled, both in a quasi-steady sense, and through the dynamics, and thus not only must the controllers be designed together, but there is the potential for synergistic control of both physical systems with the same actuators. Thus, an integrated approach must be taken to the control of the inlet and compressor *system*.

A preliminary systems analysis has been conducted by Northrop Grumman for an uninhabited combat air vehicle (UCAV). A typical serpentine inlet for this class of vehicles is shown in Figure 1; the inlet includes turning, diffusion, and a shape change in a compact configuration. The system study indicates the potential for achieving a significant reduction in vehicle TOGW if an inlet with length to diameter ratio (L/D) of 1.5 is used, rather than an L/D 3.0 inlet that is achievable with current technology. The focus of the effort in the program reported on herein is to develop technology that enables the shorter inlet to be viable. The system analysis shows that one must not only retain the pressure recovery of the unseparated inlet, but also control the compressor dynamics to allow a smaller engine to be used, operating closer to the stall boundary, while tolerating any increase in distortion or unsteadiness from the controlled aggressive inlet. The benefits study also indicates that bleed levels up to about 2% of total mass flow could be tolerated and still yield significant system benefit.

Potential actuator locations to control the compressor and separation dynamics include compressor face actuation (CFA), and separation point actuation (SPA). The overall control options for the program are laid out in Figure 2, and the possible architecture shown schematically in Figure 3. Both the control of the compressor through CFA, and of separation through SPA, have been considered previously.

	Separation Dynamics distortion, recovery & unsteadiness/inlet length	Stall Dynamics stall margin or TSFC
SPA	Direct Path	Indirect Path
CFA	Indirect Path	Direct Path

Figure 2: Matrix of control options, including both direct, and indirect control paths.

The indirect paths, control of separation using CFA, or control of stall through SPA, have not been examined. These indirect paths provide the potential for synergy if the overall dynamics can be controlled through a single set of actuation hardware. Furthermore, examining controllability also provides a means for assessing the degree of dynamic coupling between the systems. This paper provides initial results on the first row of the matrix in Figure 2, control using separation point actuation. Since prior work exists on control of separation from SPA, more emphasis will be placed on the analysis of controllability of the indirect path, from SPA to stall dynamics.

The use of air injection actuators at the compressor face to stabilize the compressor dynamics has been demonstrated successfully in multiple tests, both with steady injection and with dynamic feedback to modulate unsteady injection [3, 4]. The latter results rely on a good understanding of the compressor dynamics using a Moore-Greitzer approach [3, 5, 6], which this paper will build upon. Air injection alters the blade passage flow properties in the rotor by altering the incidence and momentum in the tip clearance region. Typical experimental results demonstrate at least a 50% reduction in the required compressor stall margin, with a maximum bleed of roughly 1.5% of the overall flow [4, 7].

Several researchers have looked at using flow control to improve the characteristics of aggressive serpentine inlet ducts. Lockheed and NASA [8] used steady injection to simulate vortex generators to modify the secondary flows introduced by turning ducts. Roughly 1% flow bleed was used on a L/D 2.5 inlet. VPI [9] demonstrated boundary layer suction or blowing on a similar geometry. Significant work has also been done using vortex generators (see [8] and references therein). Unsteady flow control techniques have received considerable attention recently and shown to be quite effective in controlling separation over two-dimensional air-

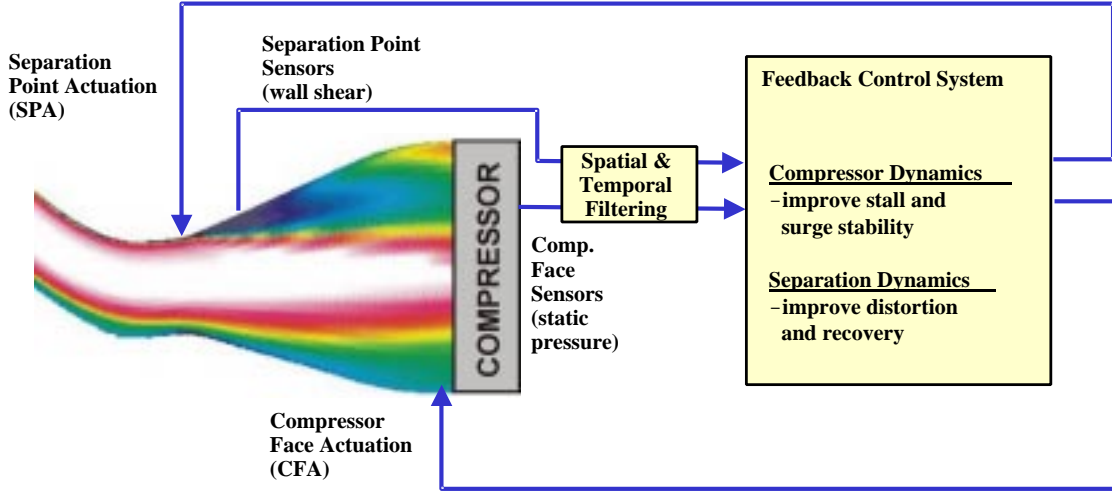


Figure 3: Control architecture. Possible actuator locations for control of the coupled inlet/compressor system include the Separation Point (SPA) and at the Compressor Face (CFA).

foils, e.g. [10, 11] and diffusers, e.g. [12, 13]. However, little work has been done using unsteady injection in complex 3-dimensional flow fields.

The remainder of this paper looks briefly at the coupled inlet/compressor dynamics, and provides a preliminary estimate of the actuator authority required to control separation using unsteady excitation at the separation point. The same actuation approach is then considered for controlling the compressor stall dynamics. The influence of separation point control on the compressor is modeled as the ability to dynamically vary the distortion at the compressor face, and this is introduced into existing Moore-Greitzer based compressor models. Analysis of controllability is then considered.

2 PHYSICS

An L/D 2.5 inlet similar to that shown in Figure 1 has been analyzed both computationally and experimentally. The geometry chosen results in some separation at test conditions representative of cruise, and although subsequent design refinement indicates the potential for achieving this inlet length without separation, the flow features of this duct can reasonably be expected to be somewhat characteristic of any more aggressive inlet. Any serpentine inlet will result in strong secondary flows from the turns [14]. The inlet under study also has a significant change in cross-sectional shape, starting from a high aspect ratio rectangular cross-section, and transitioning to circular through the diffuser. The test results indicate that at cruise, the dominant separation is at the entrance to the diffuser. The upper surface, and, to a lesser extent, the lower surface, experience significant adverse pressure gradients due to the diffusion, the cross-sectional shape change, and the turning. As the flow sepa-

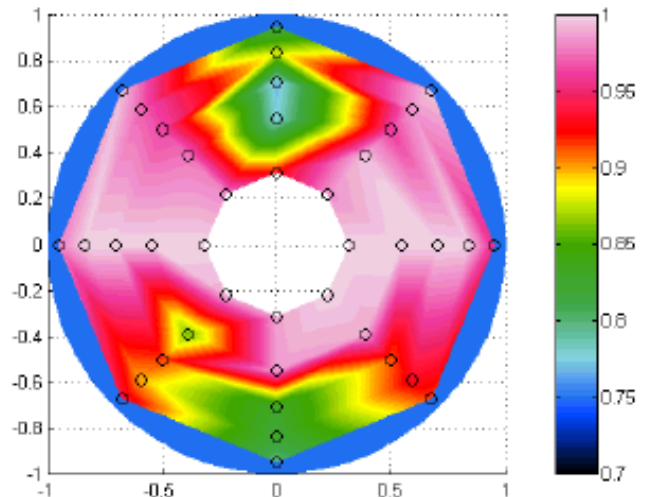


Figure 4: Measured distortion at the Aerodynamic Interface Plane (AIP). The anomolous point in the lower left quadrant is due to a bad pressure sensor.

rates on the upper surface, attached flow rushes in from the side, resulting in a detached pair of streamwise vortices and corresponding pressure distortion that persist down to the AIP, as shown in Figure 4. Thus significant 3-dimensional structures exist both upstream of separation, due to secondary flows, and downstream of the separation, due to the circumferential variation in pressure gradient around the duct.

The primary influence of separation structures on compressor performance is through the total pressure distortion pattern that results. As shown in Figure 4, total pressure at

the compressor face is severely nonuniform. The compressor sees this non-uniformity as a circumferential variation in blade incidence². If the compressor has no IGVs, this incidence variation is experienced directly by the rotor as an unsteady forcing function, as the blades rotate through the distorted inlet flow. Even with IGVs, total pressure distortion impacts compressor stability dramatically, by altering the compressor’s stall dynamics.

The term ‘stall dynamics’ refers to the time evolution of perturbations on the steady flow through the compressor [5, 6]. These perturbations take the form of cells of nonuniform axial velocity, which typically rotate at a fraction of the rotor speed. The growth of these cells to very large amplitude results in rotating stall, a debilitating compressor state consisting of a very low flow region rotating around the compressor annulus. In this region the compressor blades are stalled, blade passage blockage is high, and delivered pressure rise is very low. The overall compressor either becomes ‘hung’ in this violent state, or further degenerates into surge, a one-dimensional oscillation that can damage the engine.

The inlet section of the compressor is a boundary condition on the internal flow in the compressor, both in the steady and the unsteady sense. A steady-state inlet distortion changes the steady operating condition of the compressor, setting up a non-uniform flow field through which stall perturbations propagate [15]. This effect is invariably destabilizing, because inlet distortion is always in the form of local flow deficits. When the inlet flow is itself the result of dynamic events, such as unsteady three-dimensional separation, the *unsteady* interaction between the compressor and inlet becomes important. This interaction is less well understood, and is the subject of ongoing research.

3 CONTROL OF SEPARATION

A preliminary analysis has been done using existing data to estimate the requirements for controlling separation from the separation point for an aggressive, L/D 1.5 inlet. For cruise, the conditions at the separation point will be taken as a Mach number of 0.65, mass flow \dot{m}_t of roughly 50 kg/s and area A approximately 0.25 m².

Unsteady excitation is considered rather than steady, in order to minimize authority requirements. Existing data uses a non-dimensionalized momentum coefficient,

$$C_\mu = \frac{\rho_i h l \langle u^2 \rangle}{\rho A_s U_\infty^2} \quad (1)$$

where ρ_i and ρ are the densities of the injected and free-stream air respectively, h and l are the width and spanwise

²Note that, roughly speaking, a total pressure deficit manifests itself as a reduction in axial velocity into the compressor. The incidence of a rotating compressor blade is the vector sum of this velocity and the velocity induced by rotation. As axial velocity is reduced, blade incidence increases; at very low axial flow the blade stalls, much like an aerofoil stalls at high angle of attack.

length of the separation actuator, $\langle u^2 \rangle$ is the mean-square amplitude of the oscillatory component of injected air, A_s is the separated area, and U_∞ is the velocity at the separation point. A reference length can be defined as $x_{\text{ref}} = A_s/l$. The non-dimensionalized frequency of excitation is then given by

$$F^+ = \frac{f x_{\text{ref}}}{U_\infty} \quad (2)$$

where the optimum frequency has been shown to be near $F^+ \sim 1$ (see [10] for a thorough discussion of the impact of frequency on both preventing separation and on reattachment). Data taken at UTRC in a two-dimensional diffuser [13, Figure 7] provide a comparison of both a forced aggressive diffuser, and the best unforced diffuser. $C_\mu \sim 0.2\%$ is shown to yield comparable pressure recovery in the aggressive geometry to the pressure recovery of a longer, unseparated diffuser. Thus this authority level will be assumed to enable the more aggressive L/D 1.5 inlet to yield the same pressure recovery as the longer, unseparated, L/D 2.5 inlet. It should be noted, however, that while the pressure recovery is maintained, the distortion and unsteadiness of the unseparated inlet may not be maintained by the controlled aggressive inlet, and therefore additional control of the compressor dynamics may be required to make the overall coupled system viable.

To convert C_μ into a momentum requirement, the expected separated area must be estimated. This is based on the hypothetical L/D 1.5 inlet geometry shown in Figure 5. In the streamwise direction, the boundary layer is assumed to separate at the entrance to the diffuser, as in the current L/D 2.5 inlet, and assumed not to reattach until the AIP, as shown in the shaded region of Figure 5(a). In the spanwise direction, due to the change in shape of the duct, only the upper and lower surfaces experience adverse pressure gradients, and due to the curvature, the gradient on the upper surface is much worse than the lower. Therefore, the upper surface is assumed to separate over the spanwise length that will experience adverse pressure gradient, as shown in the shaded region in Figure 5(b). These are worst case assumptions, and the actual inlet is likely to be better, and thus to require less authority to control.

The resulting estimate of required momentum $\rho_i h l \langle u^2 \rangle$ is 30 kg m/s², much larger than in many other applications in the literature. This implies that, although many results have been obtained with zero mean injection (synthetic jet), it is doubtful whether any practical actuator could be built for this application that would have sufficient authority. While modulating steady injection has been shown [16] to be less effective than pure unsteady injection without a bias, its implementation is likely to be sufficiently easier so as to offset any penalty. Compressor bleed is available, and very high unsteady authority can be readily obtained. While the practicality of synthetic jets needs to be verified in an ultimate application, for the preliminary analysis, modulated injection will be assumed, and authority will be converted

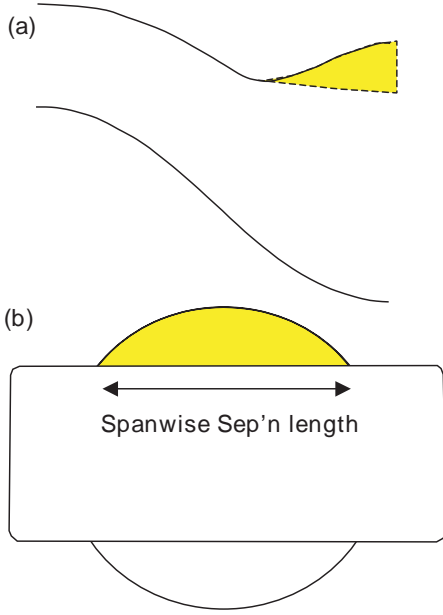


Figure 5: Expected separated area for aggressive, L/D 1.5 inlet. (a) streamwise cross-section, (b) spanwise cross-section at the entrance to the diffuser and at the AIP.

into an equivalent percentage bleed.

To convert the momentum requirement to a mass flow requirement, either the exit velocity of the injected flow, or the actuator slot width h must be specified. If the injected flow velocity varies according to $U_i = kU_\infty (1 + \sin(\omega t))$ for some k , then the momentum coefficient in Eq'n 1 can be expressed in terms of the mean mass flow injected \dot{m}_i and the total inlet mass flow \dot{m}_t as

$$C_\mu = \frac{1}{2}k \left(\frac{\dot{m}_i}{\dot{m}_t} \right) \left(\frac{A}{A_s} \right) \quad (3)$$

Choosing the mean velocity ratio k so that the peak injected flow is nearly choked at the slot exit yields a bleed requirement of 1.2% of the total duct mass flow through a 2.3 mm wide slot. While this requirement seems high, it should be noted that the L/D 1.5 inlet is extremely aggressive, the assumed separated area is likely conservative, and that with high speed flow, the ratio $\langle u^2 \rangle_i / U_\infty^2$ is constrained to be relatively low.

Existing actuator technology for unsteady flow control includes synthetic jets (demonstrated using piezoelectric [17], electro-magnetic [18], and PVDF actuation), modulated injection (using various types of air valves [19], pulsed combustion [20], or fluidic approaches), and other advanced concepts (e.g. glow discharge). The required momentum for this application is significantly higher than the authority currently obtainable with any single existing synthetic jet actuator. However, existing air valves used in compressor stability control can deliver sufficient authority with rela-

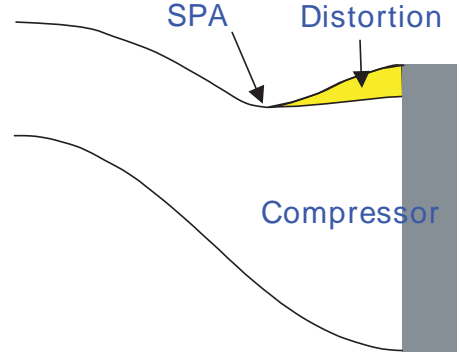


Figure 6: Impact of separation point actuation on compressor via modulation of distortion.

tively few separate devices. The Moog actuators used in [4, 7] can each deliver 13% of the requirement. Therefore, despite the high levels of authority projected by this analysis, it is expected that off the shelf actuation can be used.

The preceding authority analysis indicates that unsteady excitation to control the separation dynamics in the aggressive inlet is likely to be feasible from an actuation perspective. Additional work is required to understand the impact of three-dimensionality of the flow field on the control implementation.

4 MODELING

Forcing and control of the compressor rotating stall dynamics can be affected by various means; in this paper we investigate the feasibility of control from the separation point, via modulation of the inlet distortion. Regardless of how effective any separation control approach may be in the inlet, some residual distortion is likely to exist. Distortion can have a significant impact on stall behavior, and even steady control to vary the azimuthal distortion pattern can significantly improve stall [21]. One means by which control at the separation point can impact the compressor dynamically is by modulating the residual distortion, as indicated schematically in Figure 6. Thus, for analysis, the inlet and separation dynamics will be ignored, and the impact on the compressor dynamics of using feedback to modulate distortion will be assessed. The convective time delay between SPA and distortion at the compressor face in the L/D 1.5 duct is roughly 2 ms, while the time for a rotating stall cell to grow to full amplitude is roughly 2-3 cycles at 150 Hz, or 17 ms [4], hence ignoring the time delay is not critical to the analysis.

Previous work on compressor control has used a Moore-Greitzer approach to model the compressor dynamics [3, 6, 22, 23]. This model, shown schematically in Figure 7, has been proven quite accurate and effective. The system model includes the compressor, inlet and exit duct, and a plenum controlled by a throttle. The compressor is modeled as a

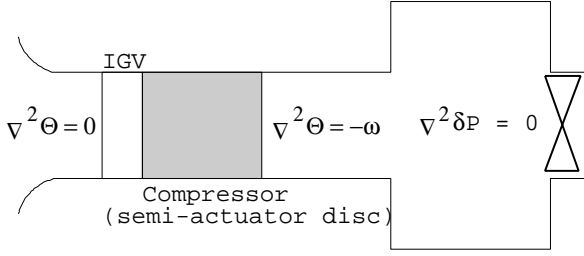


Figure 7: Schematic of Moore-Greitzer model.

semi-actuator disk. The flow upstream of the compressor is assumed to be potential. The plenum is large and acts as a mass storage device and captures the compressibility of the flow. The dynamics of the exit throttle are modeled as a pressure drop across an orifice. The compressor has a non-linear pressure rise map which is a function of the axial flow, the rotor inertia, the circumferential angle and the fluid inertia. Acceleration of the axial flow is driven by pressure rise across the compressor, which is in turn a function of the local flow. The inertial properties of the flow in the blade passages, the impedance properties of the upstream and downstream flow fields, and the inlet distortion together determine the eigenvalues of the system, which are circumferentially propagating waves. Instability of these waves results in rotating stall.

Summing the upstream, compressor, and the downstream dynamics leads to a set of PDE's:

$$\Psi(\theta, \xi) = \Psi_c(\Phi + \delta\phi) - l_c \frac{d\Phi}{d\xi} - \lambda \frac{\partial \delta\phi}{\partial \theta} - (\mu + m) \frac{\partial \delta\phi}{\partial \xi} \quad (4)$$

where Ψ is the average pressure rise coefficient, Φ is the average flow coefficient, $\delta\phi$ is the perturbation of the flow from the average, Ψ_c is the steady state compressor characteristic, γ is the throttle coefficient, and l_c , λ , m , and μ are parameters that depend on the compression system.

Mansoux et al. [6] proposed a high fidelity model by expressing higher harmonics in terms of the local flow using a discrete Fourier transform. This model takes the form

$$\dot{\phi} = \overline{E}^{-1} (-\overline{A} \cdot \phi + \Psi_c(\phi) - T \cdot \Psi) \quad (5)$$

$$\dot{\Psi} = \frac{1}{4B^2 l_c} (S \cdot \phi - \gamma \sqrt{\Psi}) \quad (6)$$

where ϕ is the vector of flow coefficients at discrete points around the annulus, \overline{A} and \overline{E} transform ϕ into and out of the Fourier domain, $S = \frac{1}{2N+1} [1 \ 1 \dots 1]$, and $T = [1 \ 1 \dots 1]^T$. A purely Fourier description in the circumferential direction can also be adopted, although this description is most appropriate when the inlet flow is uniform [6].

To capture some of the realistic considerations, a model for the transient pressure losses across the rotor and stator is added to the collocated model [24, 25]; L_r and L_s are the

total pressure loss across rotor and stator, and L_r^{ss} and L_s^{ss} are the steady state losses.

$$\Psi_c = \Psi_c^{qs} = \Psi_c^{isen} - L_r - L_s \quad (7)$$

$$\dot{L}_r = \frac{1}{\tau_r} (L_r^{ss} - L_r) \quad (8)$$

$$L_r^{ss} = \overline{R} (\Psi_c^{isen} - \Psi_c^{qs}) \quad (9)$$

$$\dot{L}_s = \frac{1}{\tau_s} (L_s^{ss} - L_s) \quad (10)$$

$$L_s^{ss} = (1 - \overline{R}) (\Psi_c^{isen} - \Psi_c^{qs}) \quad (11)$$

The states of the resulting Moore-Greitzer description are the axial flow at discrete points around the compressor annulus, the pressure in the plenum chamber, and auxiliary states describing time lags in the development of losses within the compressor.

The model has been extended to include the effects of distortion and its control via actuation. The inlet distortion is modeled as a distortion screen in the inlet duct and the resulting pressure loss is governed by the local flow coefficient. The distortion is modeled as an additional pressure loss at the rotor,

$$\Delta L_r^{ss} = \frac{1}{2} C_d(\theta) \phi(\theta)^2 \quad (12)$$

where $C_d < 0$ is the distortion screen parameter and its θ dependence determines the circumferential extent of the distortion.

To model the effect of SPA control, we assume that we can modulate the pressure loss due to distortion. For simplicity, we model this as a simple pressure addition at the rotor and we require that it never be larger than $C_d(\theta)\phi(\theta)^2/2$.

5 CONTROL OF STALL

Air injection immediately upstream of the compressor face has been demonstrated to be very effective in coupling with the compressor stall dynamics. Modulating the distortion should be expected to be less effective, as it only affects the local mass flow, and not the local angle of attack as air injection does. Modulating distortion should, of course, have some effect, simply because the mean distortion is being reduced. Therefore, to assess whether a dynamic feedback approach is better than simply using the available control authority to quasi-steadily minimize the distortion, the dynamic approach should be compared with the benefit obtained with the same mean, but steady reduction.

The approach taken here is to assume control (distortion reduction) dependent on the magnitude of the local flow perturbation, and to allow for a spatial lead or lag. This is roughly equivalent to varying the phase of the time dependent distortion reduction relative to the stall cell, while keeping the magnitude of the reduction constant. If the

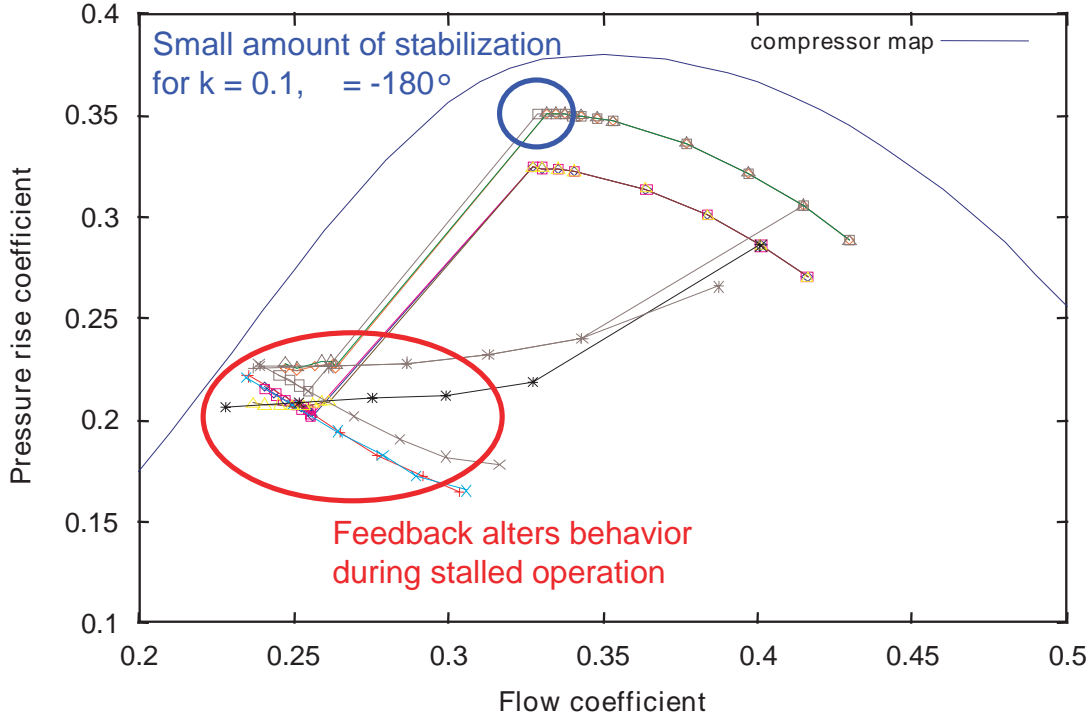


Figure 8: Simulation results. Top line shows the undistorted, uncontrolled compressor characteristic. The remaining two families of lines correspond to different control gains. Each line within each family corresponds to a different control phase.

stall margin does not depend on the phase but only on the gain, then clearly only the mean reductions are relevant.

Figure 8 shows the un-distorted compressor characteristic, and two families of controlled compressor characteristics corresponding to different gains. For the smaller gain (lower family of lines), there is roughly a 5% reduction in the mean distortion, for the larger gain (higher family), the mean reduction is roughly 50%. Within each family, the phase is varied between zero and 360° , and the resulting closed loop compressor characteristics are overplotted (not all phases are shown). At the higher gain, a very slight change in the stall point is noted, indicating a very weak dynamic controllability over stall. However, this change is negligible relative to the improvement in stall margin with the mean distortion reduction. There is also some effect on the post stall behavior, however, this effect is not useful.

The preliminary conclusion based on analysis presented herein is that the compressor stall dynamics are from a practical perspective not controllable from the separation point. From a systems perspective, these results imply that a combination of separation point and compressor face actuation may be the most viable option.

6 SUMMARY

An integrated approach for controlling coupled inlet (separation) and compressor (stall) dynamics is required to en-

able an optimized system yielding significant aircraft size reductions by reducing the engine inlet length. Preliminary analysis for controlling both separation and compressor stall dynamics using only separation point actuation has been conducted. This study indicates that dynamic controllability of the compressor via SPA is poor. While further work may revisit this conclusion using a low order integrated system model, it appears likely that compressor face actuation will be required as part of the overall control solution.

Control of separation dynamics at the separation point has been assumed to be feasible based on prior work, and a preliminary assessment of actuator authority requirements for an aggressive inlet geometry would suggest that this approach may be viable. However, significant work remains in understanding the separation dynamics, particularly due to the complex three-dimensional nature of the flow field. Furthermore, if CFA will be present to control stall dynamics, it is reasonable to ask whether these actuators could also affect the separation dynamics either by changing the downstream acoustic boundary condition, or by sending acoustic waves upstream to interact with the vorticity shedding at the separation point (as in [26]). This research is in progress.

Overall, it appears likely that by approaching the problem from an integrated perspective, a viable flow control solution can be found that will enable significant reductions in inlet length, and hence vehicle size. The optimal

mix of compressor face and separation point actuation will be experimentally determined based on a trade-off of performance, cost, weight, and system complexity.

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