

Measurements of Flow in Boundary Layer Ingesting Serpentine Inlets

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Mechanical Engineering

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December 15, 2011
Blacksburg, Virginia

Keywords: Inlet, Diffuser, Boundary Layer Ingestion, Wake Ingestion, Distortion, Flow Control

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Abstract

Highly integrated airframe-propulsion systems featuring ingestion of the airframe boundary layer offer reduced noise, emissions, and fuel consumption. Embedded engine systems are envisioned which require boundary layer ingesting (BLI) serpentine inlets to provide the needed airflow to the engine. These inlets produce distorted flow profiles that can cause aeromechanical, stability, and performance changes in embedded engines. Proper design of embedded engine systems requires understanding of the underlying fluid dynamics that occur within serpentine inlets.

A serpentine inlet was tested in a specially designed wind tunnel that simulated boundary layer ingestion in a full-scale realistic environment. The measured total pressure profiles at the inlet and exit planes of the duct, and the static pressure distributions along the walls provided useful data related to the flow in BLI serpentine inlet systems. A bleed flow control system was tested that utilized no more than 2% of the total inlet flow. Two bleed slots were employed, one near the first bend of the S-duct and one near second. The bleed system successfully reduced inlet distortions by as much as 30%, implying improvements in stall margin and engine performance.

Analysis of the wake shape entering the S-duct showed that the airframe and inlet duct are both important components of a wake-ingesting inlet/diffusion system. Shape effects and static pressure distributions determined flow transport within the serpentine inlet. Flow separation within the S-duct increased distortion at the engine inlet plane. Discussion of airframe/inlet/engine compatibility demonstrates that embedded engine systems require multi-disciplinary collaborative design efforts. An included fundamental analysis provides performance estimates and design guidelines. The ideal airframe performance improvement associated with wake-ingestion is estimated.

Acknowledgments

I wish first to thank United Technologies Research Center for the financial support of this research, without which these experiments would not have been possible. Om Sharma, Razvan Florea, and Greg Tillman of UTRC, and David Arend of NASA Glenn Research Center are gratefully acknowledged for their help and many valuable insights in developing this project. The discussions (many of which occurred on late nights and weekends) regarding every aspect of the experiment, analysis, and publications have been invaluable. This project represents a true accomplishment in the collaboration of government, industry, and academic research institutions. It has been a true privilege to work with each of you.

My sincere gratitude is offered to the members of my thesis committee: Dr. Walter O'Brien and Dr. Danesh Tafti of Virginia Tech, and Dr. Om Sharma of United Technologies Research Center. Your assistance and support are appreciated and will not be forgotten. Thank you for your dedication to both research and education.

To my friends and colleagues throughout my years at the Virginia Tech Turbomachinery and Propulsion Research Lab: Matt Perry, Jordan Farina, Kat Tran, Todd Pickering, Steven Steele, Justin Bailey, Kevin Hoopes, and Bill Schneck. Working with you has been a pleasure and privilege. I thank each of you for the support, many discussions, and extra efforts you have taken to aid me in completing my research. I will never forget practicing my first research presentation with Matt and Jordan in Denver. Justin, thank you for the help in proofreading the first (and very long-winded) draft of my thesis. Todd, Steve, Justin, and Kevin, I cannot count the number of times you showed up at the lab when I was at my wits end and helped with construction and programming. We have been a great team, and I hope for a lifetime of continued collaboration with each of you.

To Bruce Cambata and Joe Garst of Electric Jet: Thank you for the opportunity to work with you as an undergraduate on the hydrogen engine. It was through that project that I first caught the "propulsion bug," and found my passion for the field.

To Bill Schneck: From the beginning of my time as a graduate student, you have been my truest and most dedicated friend. You have selflessly aided me with countless homework assignments, data collection programs, instrumentation issues, construction projects, and publications. There has been no time, day or night, that I could not call you and have a set of helping hands 15 minutes later. Along the way we've managed to have a lot of fun, and each grown as a result. No amount of words can ever thank you for what you have done for

me.

To my advisor, mentor, and friend, Dr. Walter O'Brien: Your leadership and passion are an inspiration to me and your students. Thank you for the late nights, weekends, and even holidays that you have sacrificed to help me reach my goals. Your support over the years will never be forgotten, and I count it one of the great honors of my life to call myself one of "O'Brien's boys." Your example and personal interest in your students has given me this goal for my career: To be as excellent a researcher, educator, and person as you.

To my parents, Brian and Andrea Ferrar, and my sister Lindsey Owens: Thank you for always believing in me and accepting nothing less than my best. You have rejoiced with me, suffered with me, and set an example for me in good times and bad. Mom and Dad, when I reach your age, my hope and prayer is that my children look at me with the admiration that I have for you.

To my grandpa and namesake, Maurice "Poppop" Durfee: Thank you for the years of love and support. Our many long discussions puzzling out science and life are some of my fondest memories. During my greatest challenges, you continually remind me of your favorite phrase from my childhood: "I can do that." You never doubted it, and you were right.

To my newly aquired family, Mark Santangelo, Theresa Montalbano, Granpa Paul Montalbano, and David Sherry: Thank you for your warm welcome, support, and interest in my work. You have challenged and inspired me. I am blessed to have you in my life.

Finally, to my wife, Nicole: You are my confidant, source of strength, and best friend. You have carried me through every step of the most challenging journey of my life. I could have never done this without your love and support. I dedicate this work, and my life, to you. I love you.

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Nomenclature

AIP	Aerodynamic Interface Plane
BLI	Boundary Layer Ingesting, Boundary Layer Ingestion
BWB	Blended Wing Body
C	Flow area compactness
$\frac{\Delta p_c}{p}$	Circumferential distortion intensity
$\frac{\Delta p_r}{p}$	Radial distortion intensity
η_d	Diffuser efficiency
γ	Air specific heat ratio
H	Wake shape factor
L/D	Inlet length-to-diameter ratio
M	Mach number
N	Number of AIP total pressure instrumentation rings
p	Static pressure, pa
p_0	Total pressure, pa
p_{atm}	Atmospheric pressure, pa
PAV	Ring-averaged total pressure
$PAVLOW$	Average total pressure in defect region
$PFAV$	AIP average total pressure
PSC	Power saving coefficient

R	Gas constant, $\frac{J}{kg-K}$
r_d	Diffuser total pressure recovery
S-duct	Serpentine Inlet
T_0	Total temperature, K
θ	Circumferential position, degrees
θ_i^-	Circumferential distortion extent, degrees
u	Velocity, $\frac{m}{sec}$

Chapter 1

Introduction

This experimental thesis reports the findings of flow measurements in a boundary layer ingesting serpentine inlet. The inlet chosen for the study was designed by United Technologies Research Center as a representative commercial aircraft embedded engine inlet with provisions for active bleed flow control. The experiments were conducted in a wind tunnel specially designed for the purpose at the Virginia Tech Turbomachinery and Propulsion Research Laboratory with the goals of expanding the detailed knowledge of flow behaviors related to this class of inlets and to explore the effects of flow control.

Embedded engine systems featuring ingestion of the airframe boundary layer are highly coupled with the airframe installation. The design and performance of such systems requires an integrated, system-wide approach as well as detailed understanding of each component. With this fact in mind, the following Literature Review chapter presents both the high-level propulsion airframe integration considerations and a review of published research efforts related to flow behaviors within boundary layer ingesting serpentine inlets. Following the Literature Review and introduction to the field, the two experimental studies that form the body of this work are presented. First, detailed measurement of the flow behaviors within the S-duct are presented in Chapters 4 and 5. Second, the effects of bleed flow control are presented in Chapters 6 and 7. Finally, the results of both studies and recommendations for extended research in this area are discussed in Chapters 8 and 9.

Chapter 2

Literature Review

2.1 Introduction

Modern aviation requirements challenge every aspect of air vehicle design, pushing each component and system towards their maximum theoretical performance. Future successful commercial aircraft must meet the ambitious goals of reduced noise, emissions, fuel burn, and field length. NASA has advanced goals for generation “N+1” to “N+3” aircraft, as shown in Table 1. For “N+3” commercial airplanes the goals are 42 dB, 55 LDN noise reduction at an average airport boundary, better than 75% LTO NOx emissions reduction, better than 70% fuel burn reduction, and better than 50% field length reduction [27]. In addition to these goals, design challenges facing military vehicles include survivability, affordability, and readiness [18].

Table 1: NASA ROA GOALS, [27]

Corners of the trade space	N+1 (2015 EIS)	N+2 (2020 IOC)	N+3 (2030 - 2035 EIS)
Noise	-32 dB	-42 dB	55 LDN at average airport boundary
LTO NOx Emissions	-60%	-75%	better than -75%
Aircraft Fuel Burn	-33%	-40%	better than -70%
Field Length	-33%	-50%	exploit metro-plex concepts

All aircraft, both military and commercial, ought to be viewed as products that must deliver maximum value to customers. Relevant factors include fuel consumption, weight, manufac-

turing cost, maintenance cost, reliability, noise, emissions, low-observability, and propulsion airframe integration. Operating cost is largely dependent on fuel consumption. For a commercial aircraft, a 1% reduction in fuel burn can translate to over \$1 million annual savings per engine per year [25]. Reduced weight is an ever-present issue for both military and commercial vehicles. Noise and emissions are becoming important in the commercial business, as regulations place stringent limits on vehicles with costly penalties for violations at airports. Curfews due to noise increase operation and planning costs to airlines. Emissions have also become a growing concern for a number of environmental reasons. With the continued use of carbon based fuels, only fuel burn reduction can impact CO₂ production. Nacelle diameter, length, and weight affect overall airframe size and capabilities, making propulsion airframe integration important to both military and commercial customers. Military engines also face low-observability requirements, which are greatly influenced by integration [26].

2.2 Integrated Airframe Systems

The above demands will best be met by a highly integrated vehicle, in which all components are optimized for maximum system-level performance. Engines with the best uninstalled fuel efficiency may not provide the best airplane fuel efficiency, due to installation weight and drag penalties associated with the improved fuel-efficient engines. In one study, airplane fuel efficiency decreased by 4.2% when engines with a 2.6% fuel efficiency improvement were installed [10]. Propulsion airframe integration is a key issue in modern design.

2.2.1 Commercial Blended Wing Body Concept

The commercial blended wing body (BWB) subsonic transport is an integrated configuration that shows promise for achieving the above goals. The interaction of the basic disciplines is unusually strong and conventional design approaches are insufficient. In such architectures, the airframe must function as a fuselage, wing, inlet for the engines, and pitch control surface. The system studies presented below indicate that the BWB offers improvements over traditional “tube and wing” airplanes in safety, weight, lift-to-drag ratio, noise, and fuel burn. Fuel burn reductions lead directly to decreased emissions as well.

Configuration effects show the possibility of 32% reduced fuel burn for a BWB utilizing podded engines mounted on pylons above the aft upper surface of the vehicle [23]. In a NASA/Boeing study, the BWB configuration was shown to reduce fuel burn by 20% relative to the current 747-400 [10].

The blended wing body airframe architecture offers additional propulsion airframe integration opportunities that further improve performance. Weight and balance requirements position the engines near the aft of the vehicle. The possibility of highly integrated or embedded engines arises, and the opportunity to ingest the airframe boundary layer and re-energize



Figure 1: NASA BWB, [21]

the wake with the thrust stream becomes available. Figure 1 provides an illustration of the commercial BWB concept with embedded engines. Embedded boundary layer ingesting (BLI) engines can provide improved propulsive efficiency by reducing the ram drag, provided the inlets can be designed to feed the engine uniform flow with efficient pressure recovery [23]. BLI combined with other airframe technology improvements and advanced integrated propulsion systems lead to a striking estimated mission fuel consumption improvement of 42% [10]. The predicted impact of these technologies on performance is summarized in the chart shown in Figure 2.

The only way to achieve the substantial vehicle-level performance improvements discussed above is through the implementation of highly integrated propulsion systems and airframes. The entire vehicle must be optimized for system-wide performance across each of the design goals. This optimization requires trade studies to arrive at the best configuration, and parameters such as uninstalled performance become only a component of overall performance. Concepts that simultaneously improve performance over each of the categories of noise, observability, emissions, and fuel burn will likely result in the best configuration, and ought to be pursued. Highly integrated or embedded propulsion systems show promise in all of these areas.

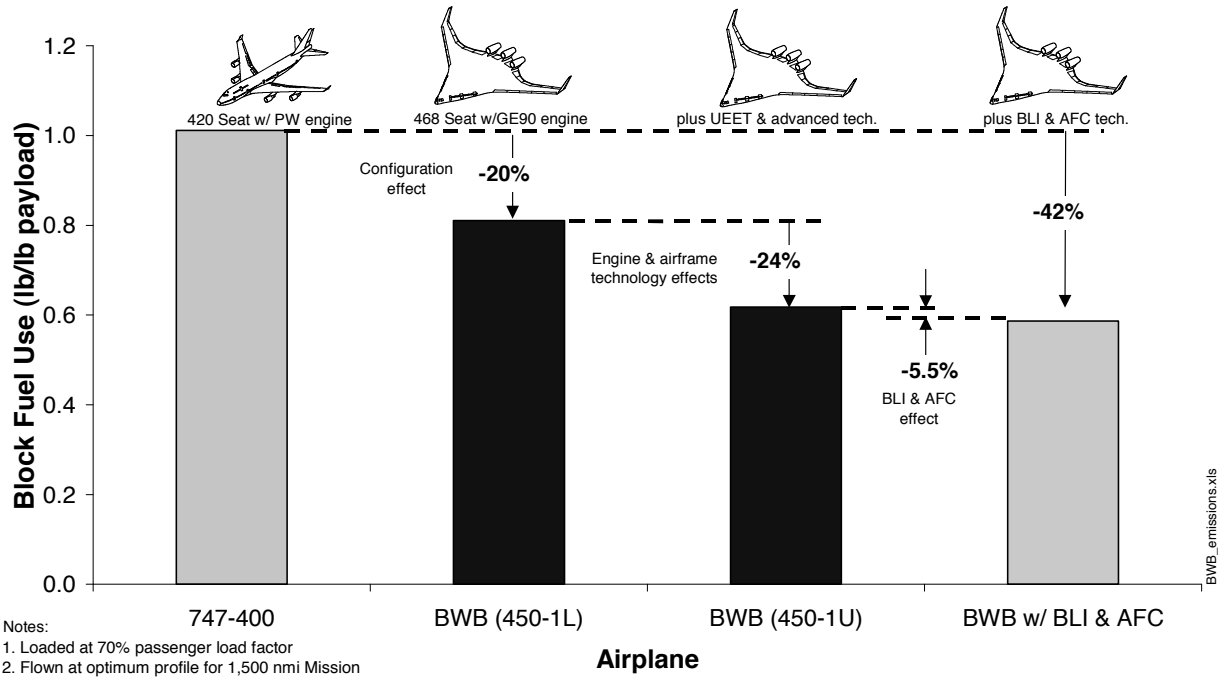


Figure 2: Predicted BWB Fuel Efficiency, [10]

2.3 Highly Integrated Propulsion Systems

Embedded propulsion systems move the engines from their traditional pylon-mounted position on the wing and partially or completely bury them within the airframe, as shown in the schematic of Figure 3. This significant change in architecture has been shown to have benefits in noise, observability, emissions, and fuel burn [21]. A primary design challenge for embedded engines is the supply of inlet air required for operation. Typically, the inlets for embedded engines are serpentine in shape and scoop inlet air and deliver it to the engine. The use of S-shaped inlets for embedded engine systems is not new for either military or commercial applications. The new generation of military aircraft including the F-22, Joint Strike Fighter, and F-117 utilize integrated engine systems with serpentine-shaped inlet ducts [4]. Commercial vehicles such as the Boeing 727 and the Lockheed L-1011 utilized serpentine inlets as well [8].

The high degree of coupling between the airframe, installation, and engine systems at all operating conditions of the aircraft complicate performance analysis [29]. The airframe can be considered part of the propulsion system because the flow over the airframe affects engine performance, and engine conditions affect the flow over the airframe. Thus, the uninstalled performance of the engine or airframe has reduced significance and an integrated, iterative analysis is required early in the design process [12]. Propulsion systems and airframes for such systems cannot be designed independently, with propulsion treated as a commodity to

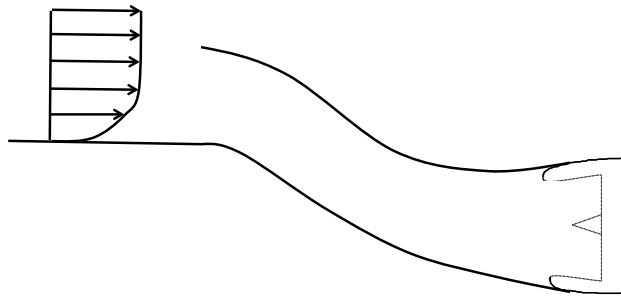


Figure 3: Boundary Layer Ingesting Embedded Engine

be purchased and installed on a vehicle. Rather, the two systems must be developed with close collaboration to achieve the optimum result.

2.3.1 Embedded Engine Operating Environment

Embedded propulsion systems operate in an environment very different from traditional pylon-mounted engines. Pylon-mounted engine systems are positioned such that the inlet ingests only undisturbed free stream air. In contrast, highly integrated propulsion systems are placed in locations that subject the inlet flow to non-uniformities caused by interaction with the aircraft surface [4]. This flow can be very different from free stream air, caused by the upper surface boundary layer and inviscid flow produced over the airfoil-shaped body of the BWB airplane [22]. The boundary layer is expected to be on the order of 30% of the inlet throat height [28]. The aft placement of the engine positions the inlet in the path of this flow, as shown in Figure 3 [4]. Although these non-uniformities persist throughout the entire operating range of the aircraft, the flow has been shown to remain attached and provide a nearly constant flow environment for engine inlets [23].

2.3.2 Benefits of Boundary Layer Ingestion

Embedded boundary layer ingesting engines have been shown to improve vehicle performance in the areas of noise, observability, fuel consumption, and emissions. Noise improvements result from airframe shielding and reduced jet velocities [17]. The high degree of turning in the serpentine inlet reduces the radar cross-section of the engine by hiding it from direct line of sight [6]. Fuel consumption is reduced by the decreased propulsive power requirement associated with drag reduction [12], wake recovery [32], and reduced propulsive work requirements [29]. The fuel consumption benefits can be substantial, depending on the amount of BLI and the spanwise portion of the airframe over which BLI is applied. The benefit has been shown to improve fuel consumption as much as 10%. Depending on engine parameters such as bypass ratio, the improvement can be on the order of 15-20% [28]. Emission improvements follow as a result of lower fuel burn.

2.4 Details of Flow within Boundary Layer Ingesting Serpentine Inlets

Inlets for subsonic, pylon-mounted engines typically have a pressure recovery of 98% or better. Any pressure recovery losses for these traditional inlets are dominated by friction drag and lip separation at off-design conditions. Boundary layer ingesting serpentine inlets introduce additional losses to inlet performance as a result of BLI and duct curvature. The inlet aerodynamics are considerably more complex due to thick boundary layers near separation approaching the inlet, wing/body shocks at transonic speeds, and adverse pressure gradients caused by wing/body closure and inlet blockage [8].

As the boundary layer is ingested the flow changes from external to internal, and flow area blockage dominates inlet behavior. The blockage can be quantified by the displacement thickness of the fuselage boundary layer. This blockage is much larger than any due to the wall boundary layers within the duct and has a major role on the achievable flow rate and fan pressure rise for a given engine thrust [29]. The airframe boundary layer can be on the order of half of the total engine diameter leading to a large momentum thickness to inlet height ratio. The kinetic energy of the inlet air is reduced, presenting a challenge as the flow attempts to negotiate the curvature of the inlet. A blended wing body vehicle is predicted to have a turbulent boundary layer with a high shape factor, on the order of 2.0. The degraded condition of the airframe boundary layer will cause it to easily separate once it encounters the aggressive turning and adverse pressure gradients of a diffusing serpentine inlet [4]. The presence of the inlet has also been observed to impose strong pressure gradients on the flow developing over the wing, further altering the characteristics of the ingested flow [17]. The airframe and serpentine inlet function as a highly coupled system, in which the performance of each significantly affects the other.

The complex inlet aerodynamics for BLI serpentine inlets presents two major challenges to propulsion system design. Inlets must be capable of providing both acceptable *distortion levels* and high *total pressure recovery* to the embedded engine [14].

2.4.1 Inlet Distortion

When considering a BLI serpentine inlet system, the flow presented to an embedded engine can be severely *distorted*, with regions of low total pressure, non-uniform velocities, and swirl that will influence engine performance. These distortions are results of separations at the cowl lip, ingested low momentum boundary layer flow and other upstream disturbances, internal flow separation, and serpentine duct diffuser effects such as secondary or cross flows [5]. Distorted flow at the engine face or aerodynamic interface plane (AIP) drives aeromechanical, stability, operability, and acoustic issues within the fan and compression system [15].

Two categories of distortion of particular importance to engine operation are circumferential and radial total pressure distortions. Both represent regions of non-uniform total pressure deficits. A circumferential distortion is one in which the total pressure varies in the angular or circumferential direction. A radial distortion is characterized by variations in total pressure in the radial direction across the span of the blade from root to tip. A typical BLI S-duct AIP total pressure profile includes regions of high and low total pressures distributed circumferentially about the flow plane. The upper half of the AIP profile consists of high pressure levels that represent undistorted inlet flow. The lower half of the AIP exhibits low pressure regions characteristic of the ingested low momentum airframe boundary layer [28]. The BLI inlet may also produce varying circumferential velocities (swirl) producing another type of distortion. Figure 4 provides characteristic circumferential and radial total pressure profiles.

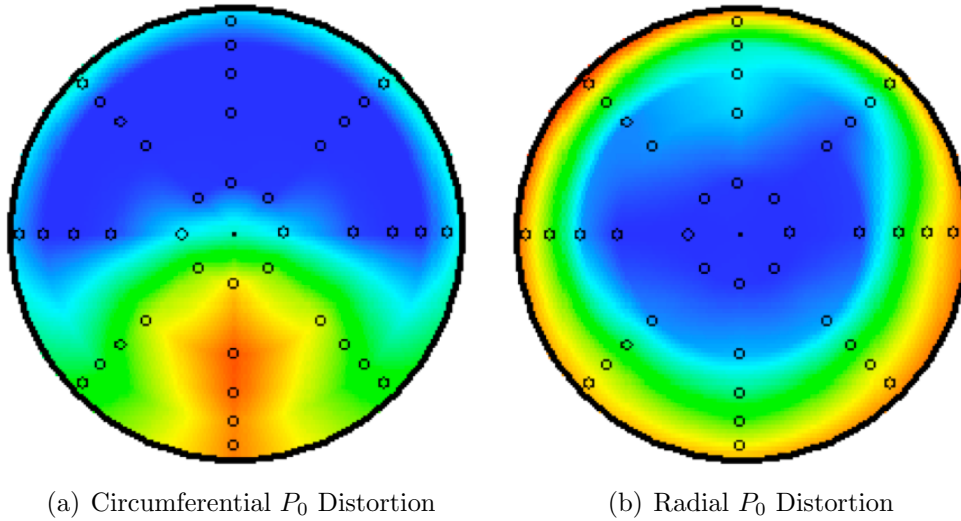


Figure 4: Typical AIP Total Pressures for BLI S-ducts, [28]

2.4.2 Separation Effects within BLI S-ducts

Severe curvature, diffusion, and inlet lip effects commonly cause flow separation and associated *total pressure losses* within serpentine inlets. These effects often superpose, leading to a challenging flow environment. The curvature due to offset can lead to two separation regions, worsened by the amount of offset. Generally, separation occurs at the first turn of the S-duct on the bottom face, as shown in the total pressure plot of Figure 5. This separation is a result of low-momentum flow attempting to accelerate over the curved wall surface [30]. The top surface of the second bend often leads to a separated region as well [14]. This separation can be smaller than the first, and difficult to detect [1].

Both separations are caused by a mechanism similar to the flow separation within a pipe [30].

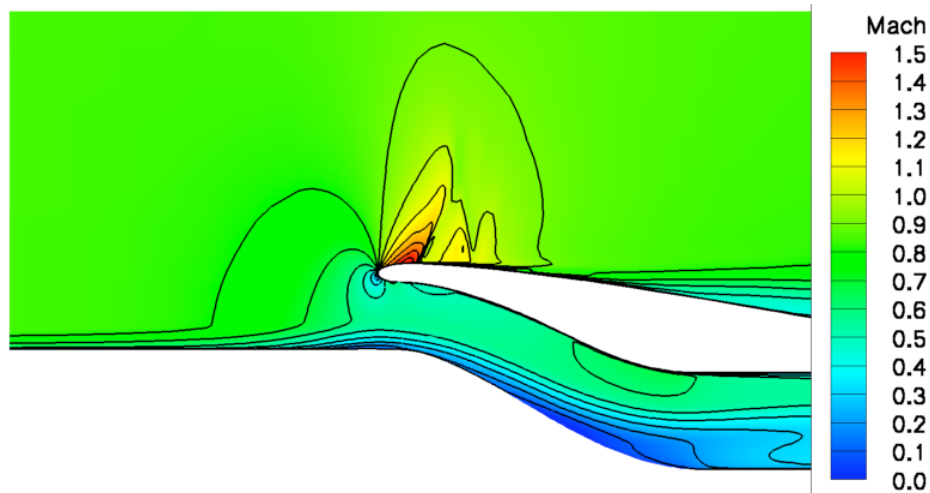


Figure 5: Large separation occurs on the lower surface of a BLI S-duct, [1]

Plateaus in wall static pressure indicate a flow separation, degrading diffuser performance for the streamwise distance of the separation. The separation has been shown to be an effect of offset, as a straight duct in similar operating conditions does not exhibit either separation. These separations result in large areas of low energy fluid at the AIP. The pressure deficit region at the bottom of the AIP due to the ingested boundary layer is worsened by the massive separation occurring at the first bend [4].

Diffusion within any inlet can lead to separation if the rate of diffusion is not carefully managed. As the flow decelerates it experiences a significant adverse pressure gradient that can stagnate the low-momentum boundary layer flow, forming a blockage and separation “bubble” [19]. The same effect occurs within serpentine inlets, and separation pockets have been observed in regions of high diffusion rate [3]. Finally, lip separation is common at off-design operation for all inlets. Once again, the effects of BLI and duct curvature worsen the issue, especially at low power settings [1].

2.4.3 Secondary Flow Considerations

Secondary or cross flows are common within serpentine inlets as a result of centerline offset and flow turning. These rotational flows are a major cause of pressure loss and distortion at the engine face, particularly circumferential distortion [5]. Several sources of secondary flows exist within S-duct inlets. First, secondary flows form at the inlet face of the duct along the corners where the duct lip meets the airframe surface [14]. Flow approaching the corner must accelerate around the inlet lip, causing a transverse flow velocity near the corner and creating a horseshoe vortex emanating from the inlet-airframe intersection, as shown in the “oil streak” plot of Figure 6 [3]. Even without BLI, a large defect region related to separation (as discussed above) and two defect regions (so-called “kidney beans”) traced to

vortices propagating from the acute inlet aperture corners can exist [18].

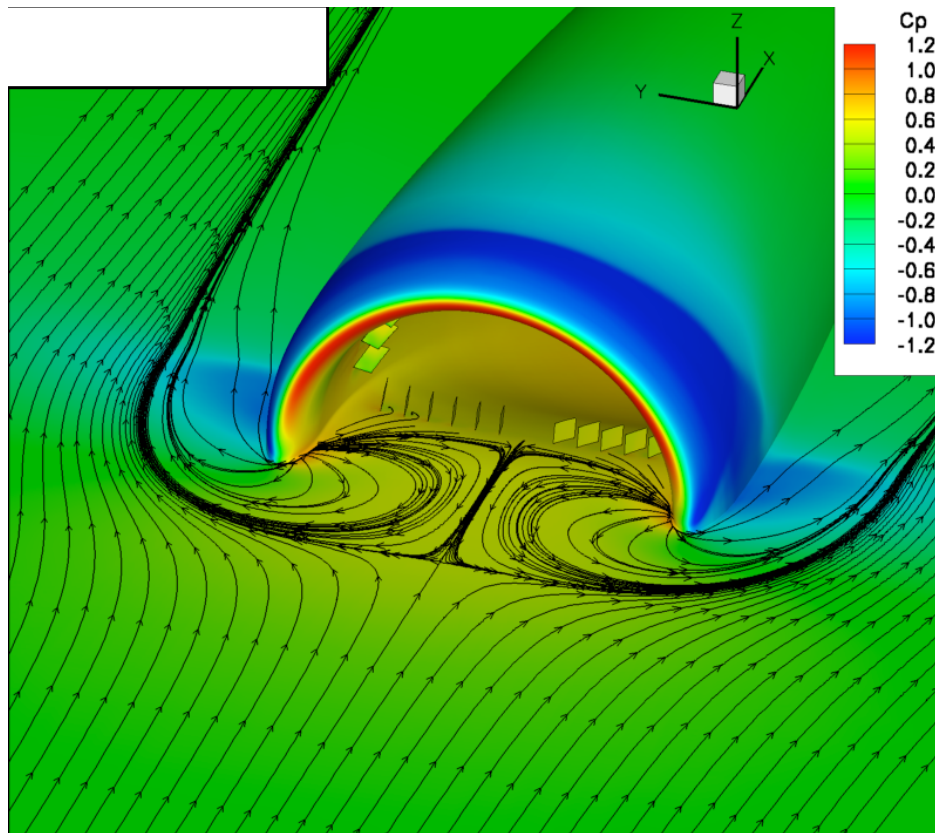


Figure 6: Vortex formation at the inlet lip/airframe interface, [1]

Duct offset is another source of significant secondary flows. A centrifugal force is generated when the fast moving core fluid negotiates a corner within the duct. A pressure differential is produced between the outside and inside of the bend that pushes fluid towards the inside of the bend [4].

Duct turning produces swirl because the centrifugal forces set up a transverse pressure distribution that moves the low energy duct wall boundary layer fluid towards the convex side of the curve and the high energy core flow towards the concave side. In general, inlet swirl patterns form as a superposition of bulk and twin swirl. Bulk, or mean, swirl is produced when a region of low energy (total pressure) is located in one position of the duct perimeter. This low energy region is typically due to a separation, and is very sensitive to flight condition and inlet installation. The flight condition and installation affect the circumferential location and severity of these flow separations, which may or may not exist for all operating conditions [18].

Twin swirl consists of two counter rotating components in the duct cross-section. Twin swirl is produced in all curved ducts as a result of centrifugal forces pushing the high energy core flow towards the outside of the curve. The motion of the high energy flow forces the wall

boundary layer flow around the perimeter to move inward [18]. The first bend in the S-duct creates a top to bottom pressure differential that forces flow along the duct wall [8]. These transverse velocities result in the formation of a pair of counter-rotating vortices [5].

With boundary layer ingestion, the formation of the vortices has additional effects. The secondary flows tend to migrate the duct wall boundary layer towards the low-pressure side of the bend (bottom of the first bend, for example) [8]. With BLI, the low momentum ingested airframe boundary layer “pools” at the bottom of the inlet, concentrating the low total pressure region over the lower half of the intake [28]. The airframe boundary layer’s slower velocity produces a smaller centrifugal force than the higher energy core flow. The balance of the forces will migrate it along the walls towards the inside of the bend more readily than the core flow. The twin swirl vortices collect the ingested boundary layer into a pocket located near the bottom wall of the duct and bottom center of the AIP. Forcing the ingested boundary layer to follow the curvature of the duct places low energy flow in a region of high wall turning, increasing the tendency of separation.

The accumulation of the boundary layer fluid at the inside of a bend will try to replace and push fluid already there away from the wall toward the outside of the bend. This collection of low energy flow in the middle of the duct produces a lift-off effect or separation of the core flow [8]. The result is that the secondary flows produced by duct curvature wrap the ingested boundary layer into a packet and lift it off the lower duct wall, placing it as a circular region raised off of the lower edge of the AIP. AIP contours show low energy flow collecting in the middle of the duct and eventually lifting off the surface towards the fan face, as shown in the plots of Figure 7 [4]. The separation is a three-dimensional phenomenon [5].

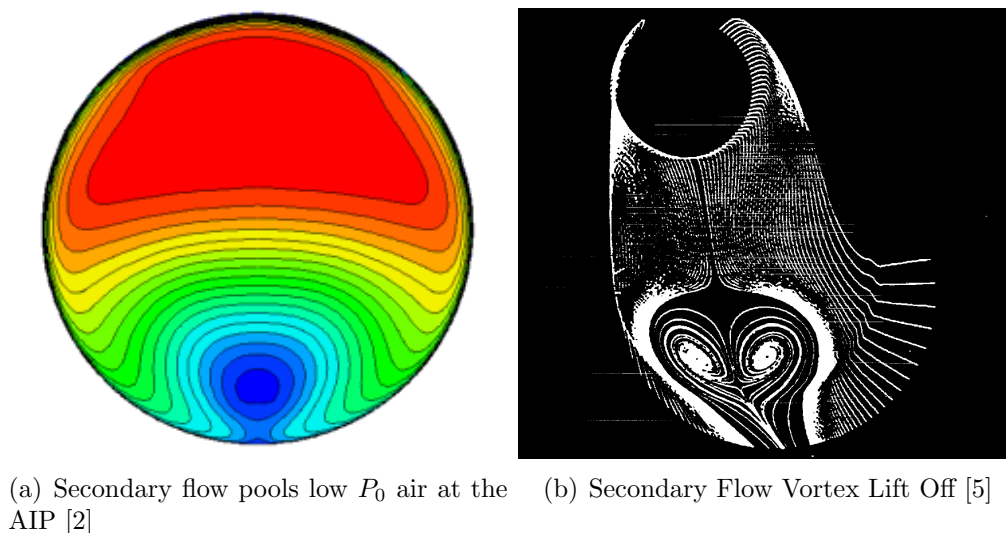


Figure 7: Secondary Flow Vortex Lift Off

The expectation is that the second bend of the duct would cause flow curvature in an opposed sense to the vortices produced by the first bend. The secondary flows generated by the second

bend should cancel those generated by the first. However, strong secondary flows persisting into the AIP have been observed with no cancellation effect. The migration of the low speed fluid has an irreversible nature, and the ingested boundary layer continues to accumulate towards the center of the S-duct [4].

Duct offset is the most important parameter governing the strength of the secondary flow. These secondary flows influence the transport of the ingested boundary layer, and enhance mixing of the boundary layer with the high-energy core flow. This mixing has a substantial negative impact on pressure recovery, and the vortices pose additional engine performance challenges [29]. Typically, Gerlach shaping is utilized in the design of S-duct diffuser cross-sections to help control the secondary flows [8].

2.4.4 Short, Aggressive Serpentine Inlets

Propulsion airframe integration considerations drive the current research focus towards shorter serpentine inlets with an aggressive centerline offset [30]. BLI embedded engine systems are so highly integrated with the airframe that inlet size becomes a dominant factor in the overall aircraft configuration. Longer S-ducts succeed in avoiding significant losses and AIP distortions as a result of gentler offset and flow turning. Low-distortion serpentine inlets can be designed when sufficient length is available, i.e. an $L/D > 2.5$. However, inlet length is a significant challenge for propulsion airframe integration. Long inlets significantly increase the size and weight of the overall system and limit vehicle performance [14]. Longer ducts result in a large engine overhang from the trailing edge of the airframe, increasing exposed wetted surface area. This overhang results in weight and drag increases. In one study, a drag benefit from reduced ram of 6.85% was observed. The duct was long enough to produce low amounts of distortion and total pressure loss, resulting in minimal effects on engine performance. However, due to the large amount of overhang, the net effect resulted in a 3.1% increase in fuel burn [10].

Shorter, more aggressive serpentine inlets that minimize flow distortion and maximize pressure recovery are desirable [14]. Shorter ducts aid in airframe integration and remove the embedded engine overhang. In the Daggett study [10], a shorter duct that completely removed the overhang reduced the nacelle surface area by 17%. The ram drag reduction remained significant at 5.1%. However, performance losses in the engine due to increased distortion and total pressure losses resulted in a 0.4% increase in fuel burn [10].

Distortion and total pressure loss reduction in shorter, aggressive serpentine inlets is a key to achieving the benefits of embedded BLI engine systems. The challenge arises due to high degrees of centerline offset, resulting in large adverse pressure gradients produced by wall curvature [14]. The airframe boundary layer easily separates when it encounters the adverse pressure gradients just downstream of the throat, reducing pressure recovery and increasing AIP distortions [4]. The resulting total pressure losses and inlet distortion degrade both engine and overall system performance [14].

Summarizing, BLI S-duct design goals include compactness, maximum pressure recovery, and minimal engine face distortion. The major parameters affecting performance are offset, curvature of the bends, area ratio or diffusion rate scheduling, and transition from the semicircular throat to the circular AIP flow area. Positioning the duct near the trailing edge of the aircraft takes advantage of the natural curvature of the airframe, reducing the required offset. The offset has been shown to have a significant impact on the flow characteristics upstream of the duct. The presence of the offset can generate a sharp favorable pressure gradient just upstream of the offset, improving the boundary layer profile [4]. To fully solve the flow issues within BLI S-ducts, all of the above parameters must be studied and optimized to yield a high-pressure recovery, low-distortion supply of air to the embedded engine.

2.4.5 Reference Studies of Flow within BLI S-ducts

The discussion above is primarily based on a review of the findings of three separate BLI S-duct studies [4, 14, 28]. These studies utilized both computational and experimental methods, and have generated a large amount of information pertaining to the flow characteristics of serpentine inlets. The published results of these studies are compared with the findings presented in this study in the results section. Table 2 summarizes the key geometric parameters of each inlet.

First, the study of Anabtawi [3] investigated serpentine inlets at low flight speeds. An inlet with a Stratford-like [33] diffusion rate or area schedule was tested in a wind tunnel at a free stream velocity of 18 m/s, or Mach 0.05. A semicircular duct with zero center line offset, area ratio of 1.7, and a length to exit hydraulic diameter ratio of 3 was measured ingesting a boundary layer produced by a long flat plate upstream. Boundary layer conditioning devices altered the flat plate boundary layer profile to match the expected profile of a BWB aircraft. The mass flow rate through the inlet was produced with an auxiliary blower, and the flow rate was varied for a given free stream or flight speed. Mass flow ratios of 0.88 (cruise) and 0.5 (start of decent) were measured [3].

A continuation of this study investigated a serpentine inlet under similar operating conditions [4]. The area ratio was modified to 1.34 as the cross section area transitioned from a semi-circular throat to a circular outlet. The length to hydraulic diameter was 1.75 with a 22% centerline offset normalized to length. This duct was aggressively short, but the offset was mild compared to the anticipated fully-embedded engine systems. The geometry parameters are summarized in Table 2. The combined findings of these studies are discussed above [4].

Second, a large research effort by NASA was reviewed. This study included both computational fluid dynamics models and wind tunnel testing. The inlet of primary interest has been designated NASA “Inlet A” and its design was performed by a related Boeing study. The inlet cross section varied from semi-circular at the throat to circular at the AIP, with Gerlach shaping [16] used to schedule the diffusion and manage secondary flows. A CAD-rendering of

the inlet is shown in Figure 2.8(a). Low-speed and high speed cases were modeled and tested in the NASA Langley Cryogenic wind tunnel with free stream Mach numbers ranging from 0.15 to 0.85. A flat plate boundary layer with flow conditioning was used to simulate the boundary layer at the aft of the BWB aircraft. The flow through the S-duct was produced by a pressure difference between the free stream tunnel flow and atmospheric, with the mass flow through the S-duct controlled by varying the outlet area of the S-duct flow path far downstream of the AIP [1, 8, 17, 28].

Finally, a United Technologies Research Center study was performed in collaboration with NASA and Virginia Tech. The UTRC duct was designed using a UTRC-proprietary modeling and optimization method. The duct was initially designed using inviscid streamline curvature methods that varied the geometry while maintaining pressure gradients and wall curvatures as constraints. An image of the inlet is provided in Figure 2.8(b). The inlet was then modeled using computational fluid dynamics, leading to the results discussed above [15].

The results of testing with this UTRC inlet form the body of this work.

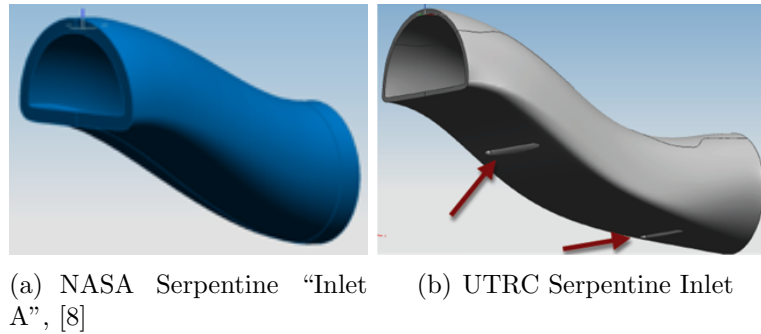


Figure 8: Research Serpentine Inlets

Table 2: Research Duct Geometries

Research Duct	Length (L/D)	Offset ($\Delta H/L$)	Area Ratio (A_0/A_i)	BL Height (δ/H_i)
Anabtawi	1.75	0.22	1.34	0.3-0.4
NASA Inlet A	3.08	0.337	1.069	0.358
UTRC Duct	3.35	0.325	1.07	0.3

2.4.6 General Trends of Flow within BLI Serpentine Inlets

The studies mentioned above lead to observations about general trends related to the flow behaviors occurring within boundary layer ingesting serpentine inlets. The trends relate to

free stream Mach number, ingested airframe boundary layer properties, duct mass flow rate, and duct curvature.

Increasing the free stream Mach number (or flight speed) results in large reductions of inlet pressure recovery. This result is typical of most inlets, but the effect is amplified by the S-duct shape and boundary layer ingestion. At low speeds, total pressure loss is primarily a function of skin friction on the duct wall. The loss in total pressure is in the range of 1%. At higher flight speeds, duct curvature and BLI effects dominate the losses. The secondary flows, ingested boundary layer, separation, and other behaviors discussed above increase the distortion and reduce total pressure recovery [8].

The result of increased mass flow through the inlet depends upon free stream Mach number as well. *Raising the duct mass flow rate decreases pressure recovery at low speeds.* At low flight speeds with low throttle (mass flow) settings the inlet is able to meet engine airflow requirements with very small losses. As the throttle (mass flow) increases the inlet area is too small to supply the engine, and the inlet must suck air into the duct from the surrounding flow field. This effect is a result of blockage due to BLI and inlet area considerations with little ram ingestion. Pulling more air from the surrounding flow environment leads to larger lip losses and pulls additional low-energy boundary layer air into the duct. The distortion is increased and the pressure recovery is reduced. Increasing mass flow through the duct at higher speeds improves pressure recovery, but the engine face distortion increases as well. The relative amount of BLI is reduced with larger mass flow, which improves recovery. However, the deficit between the ingested boundary layer and free-stream flows results in a greater total pressure deficit at the AIP [8].

Degradation of the health of the ingested airframe boundary layer is detrimental to both total pressure recovery and distortion. As the energy of the boundary layer flow is reduced, the flow becomes more susceptible to separations within the S-duct. Inlet performance is a function of the ingested boundary layer shape factor. The result is that the airframe is now part of the inlet/diffusion system and must supply a “healthy” boundary layer to the inlet with minimal upstream disturbances [8].

In general, two major features appear at the AIP of a BLI S-duct. First, a pool of low total pressure air at the AIP is the result of duct curvature effects. *The ingestion of the low energy boundary layer and secondary flows induced by S-duct geometry collect the low energy air as a pocket at the AIP plane, resulting in reduced inlet pressure recovery and increased inlet distortion.* Second, a ring of low total pressure air around the circumference of the AIP is the result of inlet lip effects.

2.5 Flow Control as an Enabling Technology

In many of the system studies presented above, the assumption is made that distortion and total pressure losses can be managed to within acceptable levels for efficient, stable engine

operation. In each study, various forms of flow control are treated as enabling technologies [4, 15, 17, 21]. Flow control can be used to minimize the losses associated with short, aggressive S-ducts [26], enhancing fan performance, high cycle fatigue performance, and operability by providing improved pressure recovery and acceptable distortion levels [1, 26]. Some studies go so far as to say that without boundary layer control, shorter inlets are not viable [14].

Returning to the Kawai/Daggett system study, active flow control to limit distortion can be used to alleviate the operability and performance issues with short S-ducts [21]. The more uniform total pressure pattern within engine operability limits provided by active flow control enabled a short inlet that reduced the nacelle surface area by 17%. The ram drag benefit remained high at 6.27%, while engine performance loss due to reduced pressure recovery was 5.1%. The net result was a 5.5% reduction in fuel burn [10]. However, this study did not account for the power requirements of an active flow control system, because the specific method of control was not defined.

2.5.1 Methods of Flow Control within Serpentine Inlets

The two primary methods for controlling flow within aggressive inlets are vortex generation and flow injection/bleed. Vortex generators can be used to counteract the natural formation of vortices and secondary flow within the duct [14]. Additionally, the ingested airframe boundary layer can be mixed into the main flow or distributed evenly around the periphery of a circular fan face. Distributing the low energy air about the perimeter of the inlet duct will reduce the large circumferential distortion encountered by the fan [3].

Vane Type Vortex Generators

Vane type vortex generators have been shown to be effective in reducing separation and inlet-generated distortion [14]. Distortion intensity reductions of 44% have been achieved [17]. In general, large vanes mix the ingested boundary layer into the higher momentum main flow. Smaller vanes distribute the ingested boundary layer rather than mix it out. Only vanes with heights on the order of the entering boundary layer thickness at the throat are effective in countering the action of the secondary flow and eliminating separation [3]. Vane flow control studies showed a substantial reduction in distortion intensity, but a pressure recovery penalty is associated with increased skin drag, mixing, and vane separation losses [4].

Jet Type Vortex Generators

Jet type vortex generators are active control devices that generate vortices by injecting flow at an angle to the main flow. These jets reduce distortion once the blowing ratio is increased

enough to balance the forces from the natural secondary flow generated by the S-shape of the inlet [1] [28]. A blowing ratio of 1-2.5% of the total airflow through the inlet is necessary to redistribute the low momentum ingested boundary layer flow and reduce circumferential distortion [28]. A minimum is reached in distortion reduction when the jets are no longer able to spread the flow due to placement. The placement and flow rates of the jets are critical to their performance. Properly implemented, the jets can reduce the circumferential distortion by up to 70% [28]. An important note is that the ingested boundary layer is not removed; rather the gradient pattern is shifted from one to another, as shown in Figure 9. The result is an increase in radial distortion intensity [28].

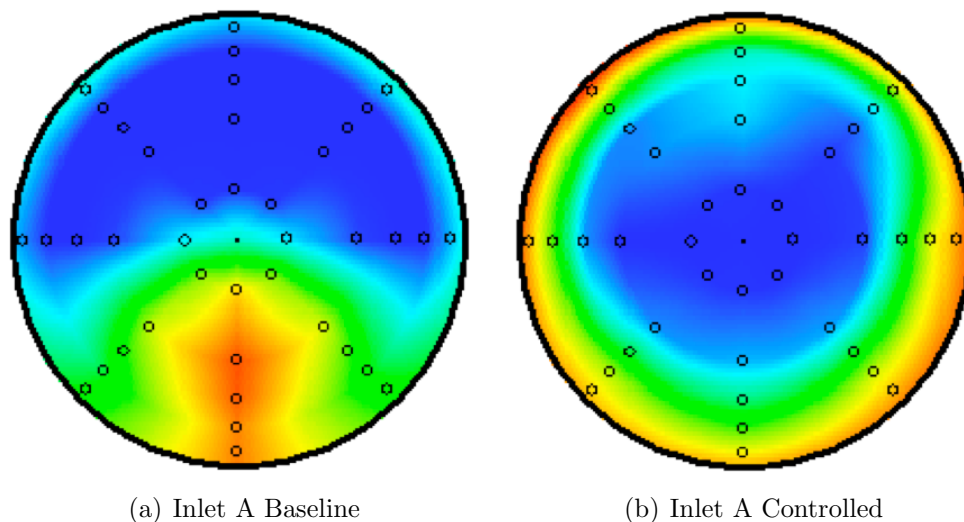


Figure 9: Effects of Vortex Flow Control [28]

The total pressure recovery decreases with increased jet blowing ratio. This penalty is a result of local flow separations and mixing of the jets with the main flow [1]. An expectation was that injection would energize the low momentum flow and increase the average total pressure at the AIP. However, the effect was to move the total pressure deficit region about the circumference of the AIP, not to remove it [1].

Flow Injection and Bleed

Flow injection can be performed in a steady or pulsed manner. Steady injection can be used to energize the boundary layer upstream of natural separation points, preventing flow separation within the S-duct [14]. Pulsed microjets have been shown to reduce the distortion from high levels to immeasurably low levels at very small blowing ratios [17].

Finally, bleed can be used to remove the lowest energy portions of the ingested boundary layer flow to prevent separation and pooling caused by secondary flows within the S-duct. Removing the low momentum flow can reduce circumferential distortion without increasing

radial distortion intensity. The filling in of the removed flow with high energy core flow results in a more uniform flow field, spreading the low total pressure regions circumferentially about the AIP [14]. An additional positive effect is that the maximum distortion level was moved closer to the wall of the duct, away from the flow that would enter the core of the engine. Preventing distortion and low total pressure air from entering the core greatly improves the performance of embedded engines.

2.5.2 Flow Control Challenges

Introducing flow control into a commercial engine is challenging. Safety requirements dictate that the engine should operate safely for sufficient periods of time in any conditions, including when flow control fails [15]. This safety consideration requires that the engine be designed with sufficient operability margin should the flow control fail [21]. Thus, flow control can provide an efficiency improvement, but cannot enable highly efficient engines that lack the sufficient stall/surge margin to operate when flow control fails.

In terms of the entire integrated system, flow control can be costly in terms of weight and power. These costs reduce potential benefits of embedded BLI engines. System-level trades of the benefits provided against associated penalties often yield little or no net system benefit for flow control [15]. In particular, active control methods require a power input and actuator weight that often out-weighs the benefits in engine performance [14]. This negative effect can be alleviated if the flow control system is designed with a system level view of the aircraft. An example is incorporating active control systems into the overall aircraft power system, such as the EC ram fan, which could be used to provide inlet suction/bleed in place of ram air to the ECS [15].

2.6 Summary and Introduction to the Presented Research

Embedded engines reduce noise, observability, fuel consumption, and emissions through substantial reductions in weight, drag, and propulsive power requirements. These benefits come as the result of reduced inlet and exhaust velocity, as well as wake recovery with minimal wasted energy addition to the propulsive stream. Benefits of the blended wing body architecture featuring embedded BLI engines have the potential to achieve over a 40% reduction in fuel burn over a current Boeing 747-400. 5.5% of the estimated fuel savings is a results of BLI benefits [10]. In order to achieve the maximum savings, serpentine inlets that supply air to the engine must be relatively short and aggressively offset. The pressure recovery penalties and high distortions due to low momentum boundary layer ingestion, secondary flows, and separations within the inlet duct present a challenging environment for highly integrated engine operation. These inlet-airframe-engine systems are highly coupled,

requiring both an integrated approach and detailed analysis of the performance of each component.

A thorough understanding of the flow behaviors within serpentine inlets will enable designers to reduce distortion and improve pressure recovery through careful inlet shaping, inlet-airframe matching, and flow control methods. To that end, this thesis presents the findings of an experimental study of a representative BLI inlet intended for commercial BWB aircraft. The two experiments conducted at the Virginia Tech Turbomachinery and Propulsion Research Laboratory measured the fundamental flow behaviors related to BLI S-ducts and the effects of active bleed flow control. The findings of the fundamental experiments show the effects of ingested profile, duct curvature, offset, and area scheduling on the development of the outlet profile. The bleed flow control tests demonstrate the ability of a small amount of bleed air to significantly reduce circumferential distortions, without increasing the radial distortion intensity. The methods and results of these experiments are presented in the following chapters: Experimental Methods, Results, Discussion, and Conclusions and Recommendations.

Chapter 3

Experimental Investigations

The research presented in this thesis consists of two experimental studies. First, detailed measurements of the flow within the UTRC S-duct provided data related to the fluid mechanics and performance of BLI serpentine inlets. The details of the experiment are presented in Chapter 4 and the results in Chapter 5. Second, flow control tests were conducted with the goal of evaluating the ability of bleed flow control to reduce AIP distortion. This experiment is presented in Chapter 6 and the results in Chapter 7. The remainder of this chapter provides details of the Virginia Tech BLI S-duct wind tunnel and general test procedures that were employed in both investigations.

3.1 BLI S-duct Wind Tunnel

Experimental research on the flow effects of serpentine inlets requires a special wind tunnel design that can simulate the wake and portion of the external flow field that would be produced in an aircraft installation. In cooperation with NASA and UTRC, Virginia Tech designed and constructed a unique BLI S-duct wind tunnel that simulates the flow profiles near the trailing edge of a subsonic airfoil. A Pratt & Whitney JT15D turbofan engine attached to a large plenum produces flow through the wind tunnel. Figure 10 provides a CAD cutaway view of the tunnel.

The flow enters the tunnel and passes over a ramp that produces the boundary layer and free stream profile of similar size and properties to that which is expected to occur near the aft end of a BWB airframe. The flow profile downstream of the ramp is representative of the environment in which an embedded BLI inlet would operate. In actual flight operation, some of the air approaching the inlet will be ingested while the remainder will be spilled. To simulate this effect in the wind tunnel, a bypass duct surrounding the BLI inlet allows the flow to split. In this way, boundary layer/wake ingestion as well as spillage occurring in an embedded engine is simulated. The flow entering the BLI inlet has a design boundary layer thickness of 30% of the inlet lip height with a free stream Mach number of 0.5. After

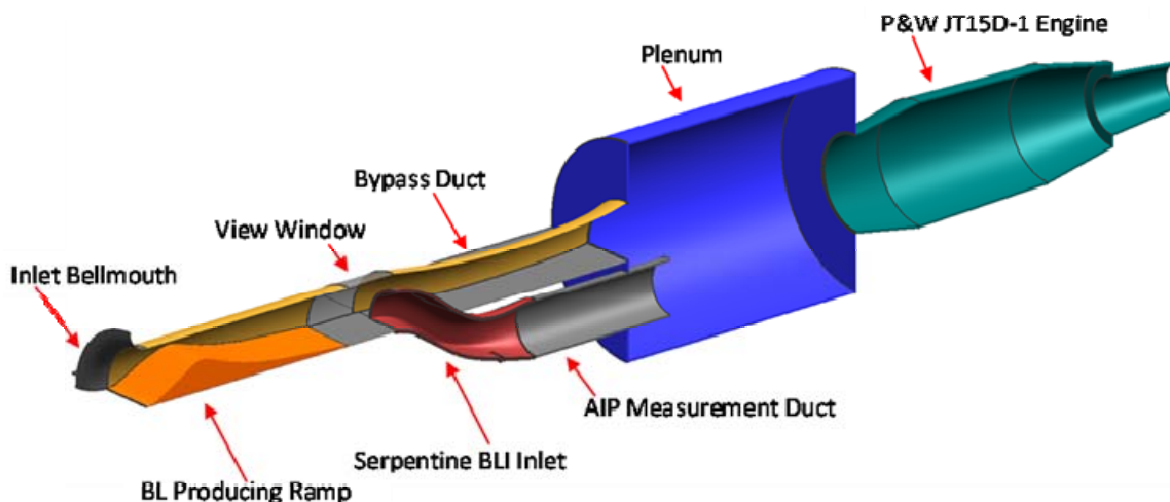


Figure 10: Virginia Tech BLI S-duct Wind Tunnel

passing through the S-duct with an AIP diameter of 12 inches and the bypass duct, the flow merges in the plenum before finally entering the engine.

3.2 Design and Construction of BLI Research Ducts

Two duct designs were utilized in the current research. A scaled version of the inlet researched by NASA was produced for initial tests in the Virginia Tech wind tunnel [7]. Limited tests were performed using NASA “Inlet A” to validate the flow fields generated by the wind tunnel. A second duct was designed using proprietary UTRC BLI S-duct design methodology. The UTRC duct was used to compare the UTRC modeling with experiment, as well as to test bleed flow control for distortion reduction. NC machining of high-density polymer foam using CAD-generated contours constructed both of the test artifacts. A coating was applied to the foam ducts to increase durability and rigidity. This method allows for rapid production of inexpensive, but accurately shaped, test articles. During testing, the pressure difference between the flow within the ducts and the surrounding atmosphere tended to collapse the inlets slightly. To alleviate this issue, a sealed extension to the plenum was placed around the outside of the inlets that equalized the pressures inside and outside of the ducts.

3.2.1 NASA Test Duct and Tunnel Validation

The NASA “Inlet A” BLI S-duct [28] was scaled to fit the Virginia Tech wind tunnel with an Aerodynamic Interface Plane (AIP) [31] diameter of 12 inches. A series of tunnel validation experiments without flow control were performed. A CAD representation of the duct is shown in Figure 11. The UTRC BLI design methodology, including CFD modeling, predicted the

flow through the NASA S-Duct. The data was compared to the published NASA data. The validation results were considered satisfactory and are presented by Hylton [20]. The design of the NASA duct is summarized in the previously presented Table 2.

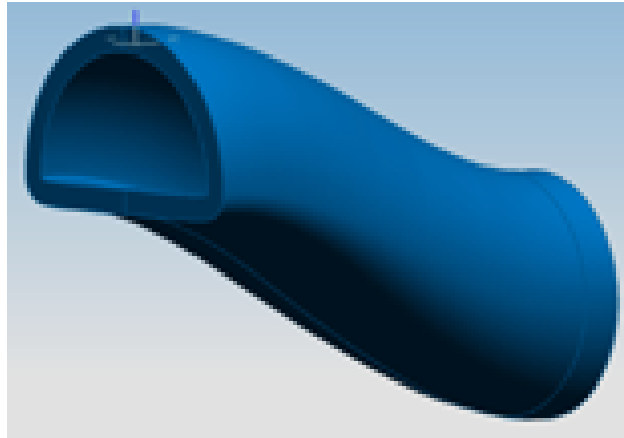


Figure 11: NASA “Inlet A”

3.2.2 UTRC Test Duct

Using UTRC CFD design techniques, an improved BLI inlet was designed. The S-duct was designed to reduce AIP distortion through improved shaping, and included provisions for active bleed flow control to prevent separation and remove the low-energy airframe boundary layer air. This serpentine inlet was constructed and tested in the Virginia Tech wind tunnel. A CAD representation of the duct is shown in Figure 12. Results from these tests form the data presented in this thesis.

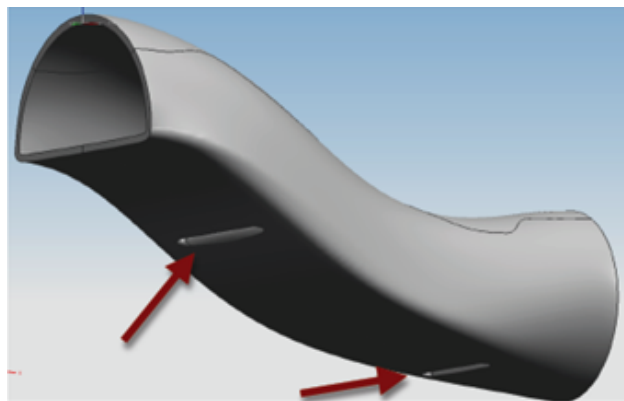


Figure 12: UTRC S-Duct with Bleed Slots

3.3 Measurement Techniques Summary

The flow fields at the throat of the BLI inlet, entrance to the bypass duct, and AIP were measured using static and total pressure probes. Additionally, the flow rate through the bleed system, and the static pressures at several locations of interest were measured. At the AIP, 40 total-pressure measurements were made using an 8-arm, 5-ring total pressure rake designed using ARP1420 guidelines [31]. Two test configurations were employed. First, the detailed measurements of flow behavior occurring within the UTRC S-duct utilized 156 total pressure probes at the S-duct throat as well as 112 wall static pressure taps. The details of this configuration are presented in Chapter 4. Second, a reduced number of throat total pressures and wall static pressures were measured to obtain data focused on the effects of flow control. The lower number of measurements enabled a greater number of test conditions involving bleed flow. The details of this experiment are provided in Chapter 6.

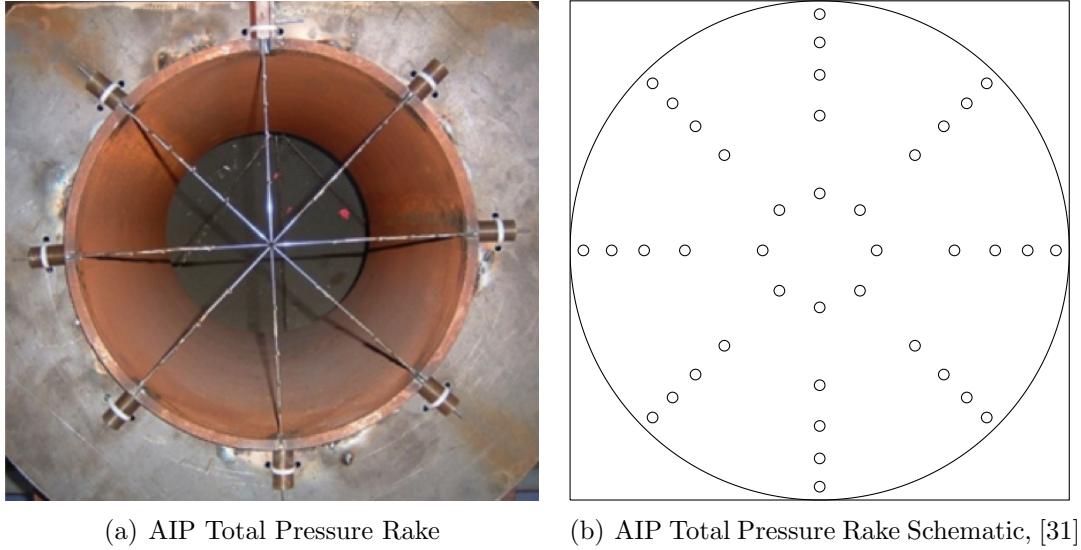
3.4 AIP Rake

The Society of Automotive Engineers Aerospace Recommended Practice ARP 1420 provides a technique for measuring and quantifying distortion intensities at the AIP and the effect on fan and compressor stall margin [31]. Following this practice, eight rakes of 5 total pressure measurement probes each were arranged at 45-degree intervals around the AIP. Each rake measured the total pressure at the centroids of 5 equal-area rings, as shown in the images of Figure 13. The 40-probe rake was accompanied by a static pressure measurement that could be used to estimate the velocities at the AIP, and thereby the mass flows through the S-duct. Reduction of the data following the methods of ARP1420 is discussed in Section 5.4.

3.5 Experimental Procedure

The measured pressures presented were produced using the apparatus described above, and recorded by a computerized digital data acquisition system. The JT15D was used as a suction source to produce flow through the tunnel and S-duct. The measurements were taken at a variety of engine speeds, which varied the flow rate through the experiment. These test conditions are listed in Table 3. The test conditions are referred to by the free stream Mach number at the serpentine duct inlet throat, computed using total pressures from an inlet rake and wall static pressures, using Equation 3.1. Details of the inlet rakes are shown in the following sections.

$$M = \sqrt{\left(\left(\frac{p_0}{p} \right)^{(\gamma-1)/\gamma} - 1 \right) \frac{2}{\gamma - 1}} \quad (3.1)$$

**Figure 13:** ARP1420 AIP Total Pressure Rake**Table 3:** Free Stream Mach Number Test Cases

Engine Speed (Fund Expt)	Free Stream Mach (Fund Expt)	Engine Speed (Flow Control Expt)	Free Stream Mach (Flow Control Expt)
55%	0.16	55%	0.20
60%	0.18	65%	0.27
65%	0.21	70%	0.32
70%	0.24	75%	0.37
75%	0.29	80%	0.43

For each case, the wind tunnel flow condition was set by engine speed. After the flow and pressures reached a steady state an 80-channel pressure scanning system recorded pressures for a sufficient period of time to obtain steady values. These recorded values were averaged over time to obtain the mean steady state values reported. In addition to the experimental measurements, the local atmospheric conditions were recorded for each case and used in calibration along with a U-Tube manometer.

Chapter 4

Experimental Methods - Fundamental

In order to gain insight into the fundamental physical behavior of the flow within the UTRC S-duct, detailed measurements of the flow entering the S-duct throat, within the inlet, and at the exit plane (AIP) were taken. These measurements were enabled by the design, construction, and implementation of an improved pressure measurement system. The experiment involved 320 pressure measurement locations which were recorded using a multi-channel pressure scanning system. Details of the measurement system are presented in Appendix A along with an uncertainty analysis. This chapter presents the additions to the instrumentation described in Chapter 3.

4.1 156-Probe Inlet Throat Rake

The first area of interest was a detailed characterization of the flow field at the inlet throat and entrance to the bypass duct. A 156-probe total pressure rake was constructed and installed at the inlet plane of the S-duct. This rake consisted of 78 probes located in the throat of the S-duct and 78 probes located in the entrance plane of the bypass duct. Each rake of 78 probes consisted of 13 arms each incorporating 6 probes evenly distributed in both the radial and circumferential directions. A photograph of this rake installed in the BLI S-duct experiment is provided in Figure 14.

The even spacing of the measurement points in the radial direction allowed a full mapping of the total pressure profile entering the duct, while the radial design ensured sufficient measurement locations near the bottom wall of the duct, as shown in the detail-view of Figure 15. These probe locations were located within the viscous boundary layer region of the flow ingested by the S-duct. The detailed measurements of the inlet and bypass duct flow profiles assisted in the calculation of an improved estimate of the mass flow through each flow path. This configuration also enabled high spatial resolution in the flow measurements near the corners of the duct, which were an area of concern in regards to the formation of corner vortices.

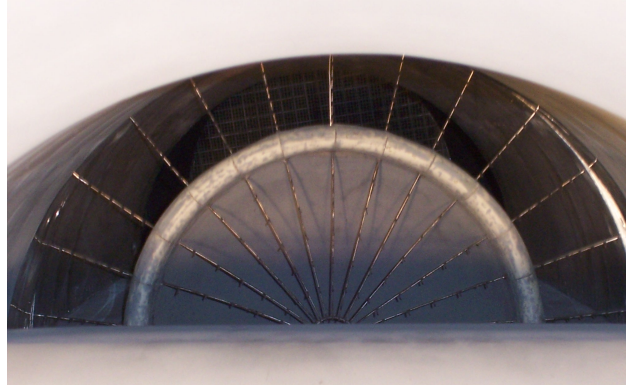


Figure 14: 78-Probe Throat and 78-Probe Bypass Total Pressure Rakes

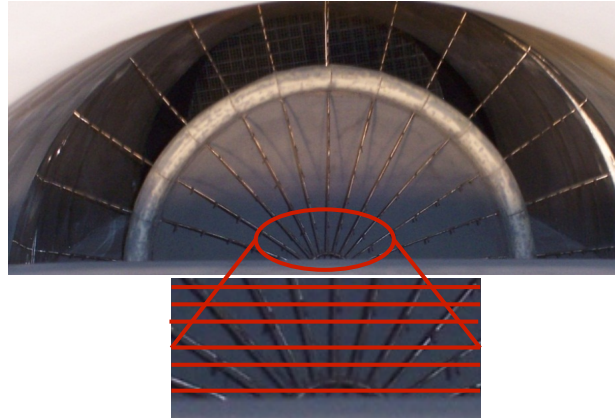


Figure 15: Throat Boundary Layer Rake Detail

4.2 S-duct Wall Static Pressure Measurements

Static pressure taps were added to the inner walls of the serpentine inlet to measure the static pressure distribution of the flow through the duct in 112 locations. These measurements were distributed along 8 streamlines of the duct, with 14 pressure taps per streamline. Figure 16 illustrates the placement of the static pressure probes along the top and bottom centerlines, as well as the distribution between them.

4.3 Additional Measurements and Schematic

The experiment was also instrumented with static pressure taps at several key tunnel locations for tunnel performance analysis. One important note is that the throat static pressure tap was located at the top of the inlet plane for an accurate measurement of the static pressure near the maximum total pressure (free stream) centerline probe. Additionally, the

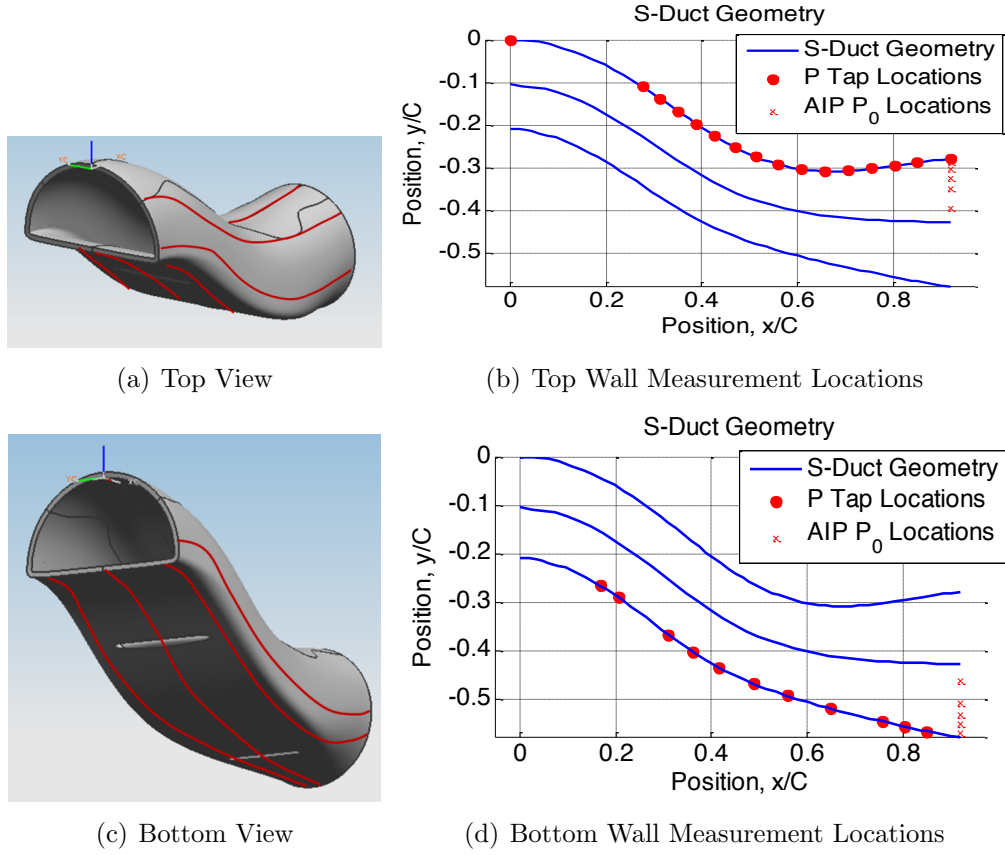


Figure 16: S-duct Wall Static Pressure Measurement Locations

static pressure tap at the AIP was located at the top ($\theta = 0^\circ$) due to installation necessity. The fundamental experimental configuration is shown schematically in Figure 17.

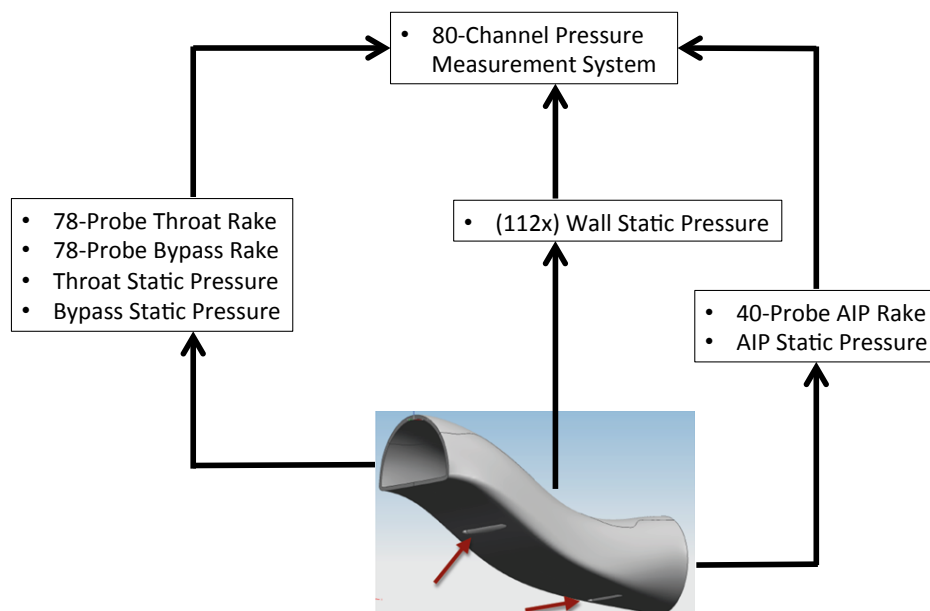


Figure 17: Fundamental Experimental Configuration Schematic

Chapter 5

Results - Fundamental

5.1 Introduction

The UTRC BLI serpentine inlet was tested in a series of experiments in the Virginia Tech Serpentine Inlet wind tunnel. This experimental configuration utilized the wind tunnel described in Chapter 3 with the additional instrumentation presented in Chapter 4 to investigate the fundamental flow behaviors within the serpentine inlet. The performance of the engine that produced the flow in the wind tunnel limited these tests to an inlet Mach number range of 0.16-0.29, as noted in Table 3. These measurements of the detailed effects of a BLI serpentine inlet on the flow and their analyses are presented in the following three sections: (1) Inlet Conditions, (2) Internal Flow Conditions, and (3) Outlet Conditions. In this manner, the flow through the BLI serpentine inlet is discussed as it progressed from the upstream flow field, through the duct, and finally to the inlet exit plane (AIP).

5.2 Inlet Conditions

Having passed over the wake-producing ramp (Figure 10), the flow reached the inlet plane of the S-duct and bypass duct. A portion of the air entered the S-duct, while the rest spilled around it and flowed through the bypass. At this plane, the flow approximated the wake-profile of an aircraft with an embedded engine. The total pressure rakes located in the throat and bypass measured the total pressure distributions, and recovery is plotted for the $M = 0.16$ and $M = 0.29$ cases in Figure 18.

As can be seen in both plots of Figure 18, the total pressure entering the serpentine inlet was non-uniform. The values were lowest near the bottom wall, and increased according to the wake flow profile of the ramp upstream. Inspection of the inlet profile shows symmetry about the vertical centerline, with the largest pressure difference about the centerline less than 0.1%. Similarly, the flow entering the bypass duct was symmetrical about the vertical

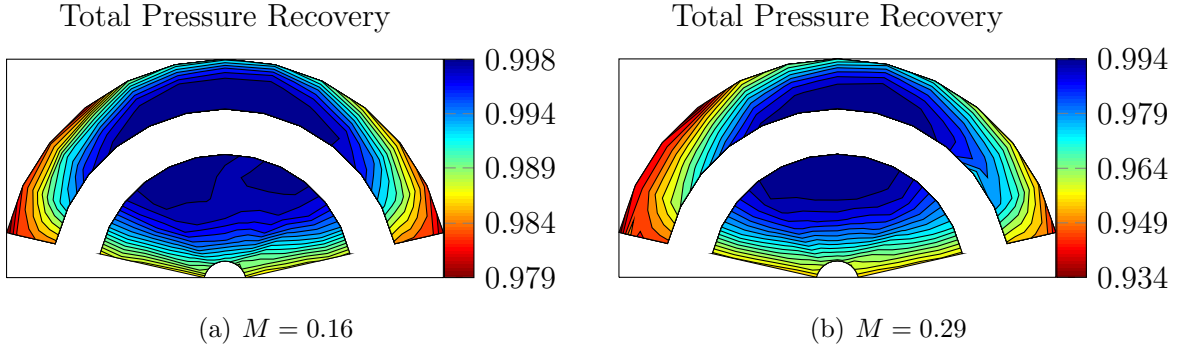


Figure 18: Throat/Bypass Total Pressure Recovery, p_0/p_{atm}

centerline, with the largest difference equal to 2.9%. Figure 19 shows a contour plot of the local symmetrical differences, normalized by the recorded value. The symmetry of the flow entering the S-duct is of importance when considering the flow over an actual aircraft. In straight flight with no crosswind, the inlet would be oriented so as to receive flow in the axial direction, and this apparatus simulated that case well.

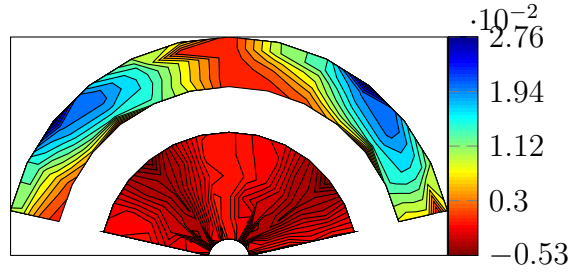


Figure 19: Inlet Total Pressure Symmetry

The average value of the total pressure at the throat compared to atmospheric pressure (the tunnel inlet free stream total pressure) is of interest because the embedded BLI engine utilizes an important new feature in its architecture. The airframe of the vehicle is now a part of the inlet diffusion system, and a meaningful portion of the deceleration of the flow from flight speed to the design inlet velocity of the engine occurs over the airframe rather than in the inlet itself. This deceleration is manifested in a reduction of the average velocity of the flow entering the S-duct, which is less than the flight speed. Any loss in total pressure from the free stream to the flow entering the engine is detrimental to performance, and ought to be minimized through design and trade-off studies.

Figure 20 displays a plot of the average total pressure ratio ($p_{0_{avg}}/p_{atm}$) at the inlet plane of the S-duct. The values of average total pressure ratio are between 0.994 and 0.976 depending on free stream Mach number. These values are fairly high, which would be associated with good airframe design. A low value of total pressure ratio represents a “lossy” inlet, before the duct is ever encountered.

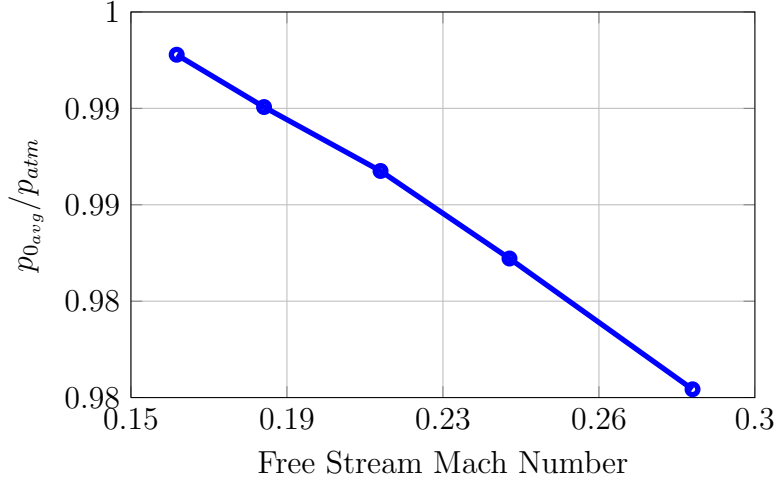


Figure 20: Throat Average Total Pressure Recovery versus Free Stream Mach Number

The overall diffuser efficiency depends on both airframe and inlet duct efficiency, and the average total pressure reaching the engine would be dependent on the total pressure ratio of the flow over the airframe as well as through the inlet duct. Equations 5.1 and 5.2 show modified definitions for diffuser pressure ratio and efficiency that account for the influence of the airframe wake/boundary layer.

$$\begin{aligned}
 r_d &= (r_{sduct}) (r_{airframe}) \\
 &= \left(\frac{p_{0_{AIP}}}{P_{0_{throat}}} \right) \left(\frac{p_{0_{throat}}}{P_{0_{\infty}}} \right)
 \end{aligned} \tag{5.1}$$

$$\eta_d = \frac{(r_d)^{(\gamma-1)/\gamma} - 1}{\frac{\gamma-1}{2}} \tag{5.2}$$

The inlet throat total pressures can be used to generate a symmetry plane (Figure 19) total pressure profile, as shown in the graph of Figure 21 for the case of $M = 0.29$. The total pressure profile clearly contains an identifiable inflection point between the wall boundary layer and the ramp wake. This inflection point represents the interface between the viscous boundary layer near the bottom wall and the non-uniform free stream profile of the wake.

The velocity profile of the flow entering the serpentine inlet is of importance because it can be used to determine the design potential and overall benefits of the embedded engine system. The computed velocity depends on both the static and total pressure values across the duct throat.

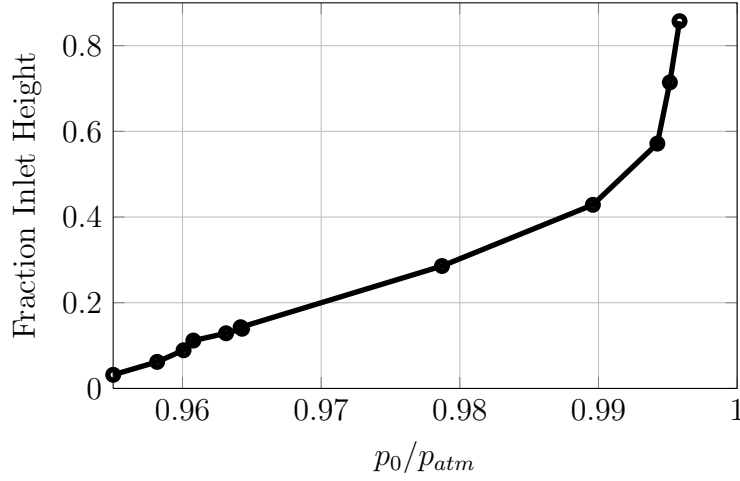


Figure 21: Centerline S-duct Throat Total Pressure Profile, $M = 0.29$ Case

The static pressure was measured at the top wall of the inlet throat plane. The static pressure variation across the duct is estimated using the following method, which enhances the calculation accuracy of the local velocities (Appendix B and C). The measured total pressure distribution within the flow, as shown in Figure 22, contains points located within the wall boundary layer.

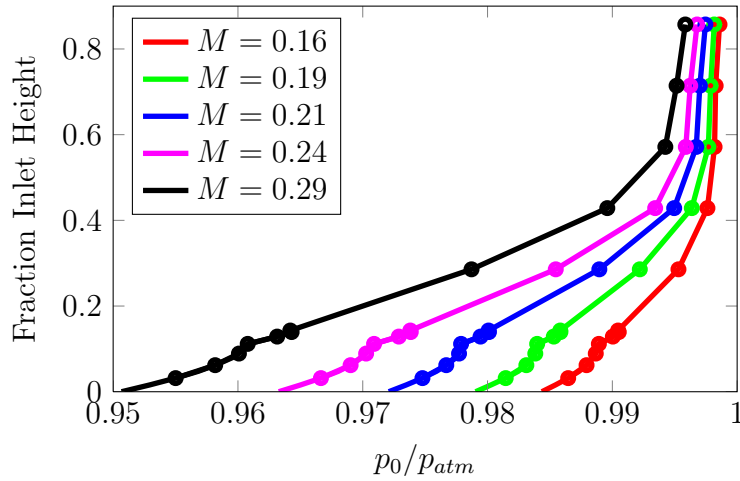


Figure 22: Centerline S-duct Throat Total Pressure Profile, extrapolated to wall for boundary layer static pressure estimate

The static pressure can be assumed to be constant in the boundary layer region. Extrapolating the total pressure curve to the wall provides an estimate of the boundary layer static pressure, based on the no-slip condition. The static pressure distribution across the entire inlet throat from top to bottom can then be interpolated to determine the local static pressure at each total pressure measurement location (Appendix B). Equations 3.1 and 5.3

compute the local velocities with improved accuracy.

$$u = M \sqrt{\frac{\gamma R T_0}{1 + \frac{\gamma-1}{2} M^2}} \quad (5.3)$$

The resulting centerline velocity profiles are shown in the plot of Figure 23 for each flow case. A discussion of the effect of error in the estimate of static pressure on local computed velocity is presented in Appendix C.

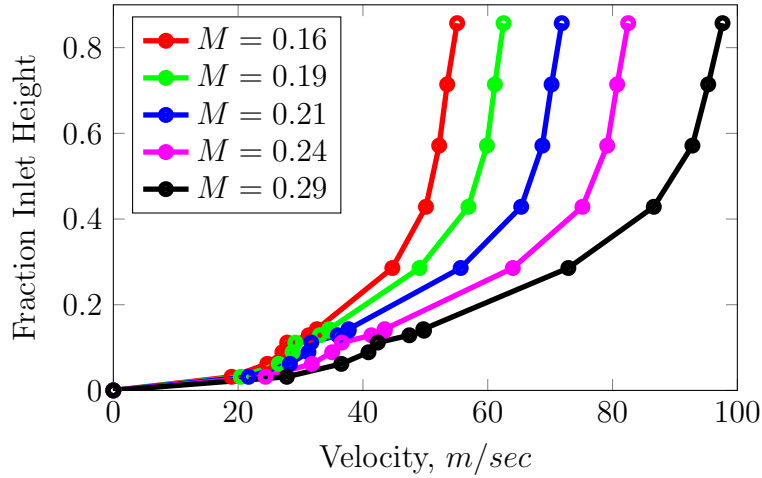


Figure 23: Centerline S-duct Throat Velocity Profiles

5.2.1 Potential Benefit of Wake Ingestion Based on Measured Data

Smith[32], in a seminal paper discussion of wake ingestion, predicted the positive effects of BLI. Following his methods the ideal performance improvement of wake ingestion can be estimated. Additionally, the wake properties are useful in describing the flow in more general terms. The wake form factors, wake displacement areas, and wake momentum areas are of particular importance because the ideal power savings associated with wake ingestion depends on these parameters. A detailed presentation of the definition and calculation of wake parameters can be found in Appendix D. Shown in Table 4 is a summary of the calculated values for the BLI tests presented here.

The power saving coefficient represents a percent reduction in power required to overcome the drag of the ingested wake. *PSC* depends heavily on wake form factor and is greatest for large wake form factors. As shown by Lieblein [24], wake form factor is greatest at the trailing edge of the airfoil. This fact means that wake ingesting propulsion systems located near the aft of the airframe have the potential to generate significant power savings. Comparing

Table 4: BL/Wake properties for each case. Values normalized by throat height

Free Stream Mach	Thickness (δ/H_i)	Displacement Area δ^*	Momentum Area Θ	Form Factor H	PSC
0.161	0.808	1.369	0.771	1.776	0.206
0.182	0.793	1.434	0.773	1.856	0.219
0.210	0.794	1.493	0.778	1.919	0.226
0.241	0.790	1.488	0.770	1.933	0.227
0.285	0.796	1.586	0.821	1.933	0.231

with Lieblein, it can be noted that the wake form factors obtained here are relatively high but are reasonable for the trailing edge of a subsonic airfoil, making the generated profile a good choice for examining S-duct performance under realistic conditions. The expected form factor at the trailing edge of the commercial BWB is $H = 2.0$ [4]. The power saving coefficient is computed using ideal assumptions, and so it sets the upper limit on the power savings possible through wake ingestion. The high value of power coefficient of $PSC = 0.23$ results in a predicted requirement of 77% power to maintain the same flight speed when wake ingestion is employed. Therefore, for an S-duct application in a wake profile such as this, the benefits can be very large.

5.3 Internal Duct Geometry and Flow Measurements

The fluid mechanics occurring within the serpentine inlet are shaped by the duct geometry itself. Inspecting the geometry along with the wall static pressure measurements leads to insights as to how the flow within the inlet is behaving. The first geometric parameter of interest is the flow area following the center streamline through the duct. Figure 24 shows a side-view of the duct and its flow area ratio distribution (area of current station/area at the throat).

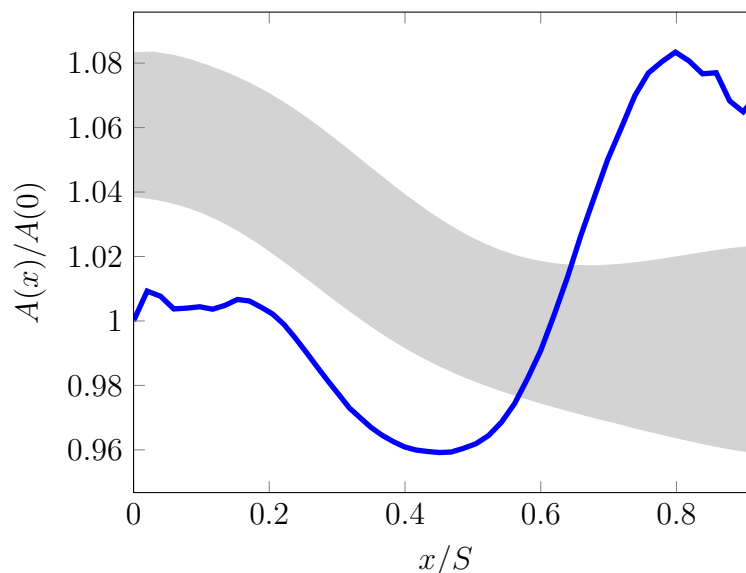


Figure 24: UTRC S-duct Area Schedule

The flow area distribution drives the static pressure gradient of the flow through the duct. As the area ratio decreases, the mean velocity must increase to satisfy continuity. This area reduction results in a favorable (negative) static pressure gradient. Similarly, when the derivative of the area ratio is greater than zero the duct is expanding and the mean velocity decreases to satisfy continuity. This area growth causes an adverse (positive) static pressure gradient. Defining sequential locations of cross-sectional areas of the S-duct at an axial location, the wall static pressure measurements at each location may be averaged to produce an average wall static pressure within the area. Figure 25 shows the variation of the average static pressure in the duct. Comparing with Figure 24, the average static pressure generally follows the expected trend based on the flow areas of the duct. These changes in flow area can be said to impose a “global” pressure gradient that affects the average static pressure of the flow.

The overall area ratio of this S-duct (exit area/inlet area) is typical for subsonic inlets, 1.07. The result is that very little diffusion occurs within the S-duct. Remembering that the inlet/diffusion system is now comprised of both the airframe wake and the S-duct, the near-unity

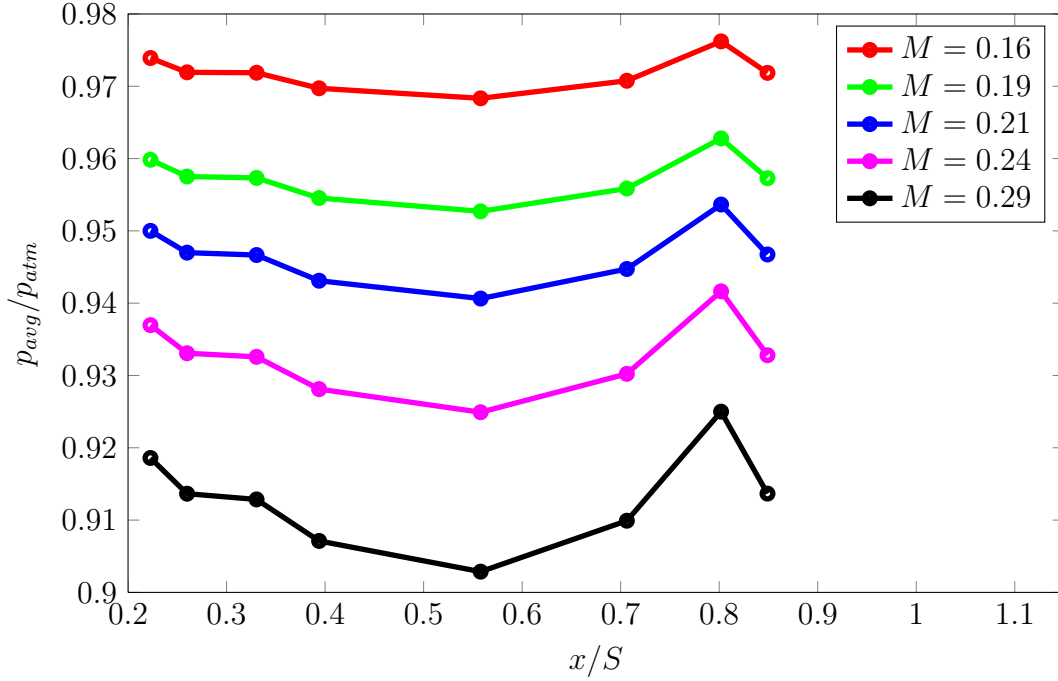


Figure 25: Average Streamwise Variation of Static Pressure

area ratio of the duct is logical. The mean velocity entering the inlet is already reduced from flight speed due to the diffusion and viscous effects over the airframe and the diffusion requirements within the inlet are reduced.

The curvature of the walls of the inlet also affects the local flow behavior. As the wall curves towards the mean flow streamline a favorable pressure gradient exists near that wall. Likewise, as the wall curves away from the mean flow streamline an adverse pressure gradient exists near that wall. In this way, the wall curvature imposes a “local” static pressure gradient. The plots of Figure 26 show the static pressure distribution along the top and bottom walls ($M = 0.29$ case) with their associated geometry.

The circled regions of Figure 26 indicate local adverse pressure gradients that are large. In each region the strong local adverse pressure gradient created by high curvature of the wall away from the mean stream line causes flow separation. Large total pressure losses in these regions reduce the inlet efficiency and total pressure ratio.

The effects of the “global” static pressure gradient associated with area change and the “local” static pressure gradient associated with wall curvature combine to dictate how the air will behave as it flows through the duct. Figure 27 shows the combined geometrical effects and the location of adverse static pressure gradients within the duct. The flow separations observed along the top and bottom of the duct are explained by the fact that both the “local” and “global” static pressure gradients are adverse in the same locations and exceed the sustainable level of the flow. The flow does not have the momentum needed to remain

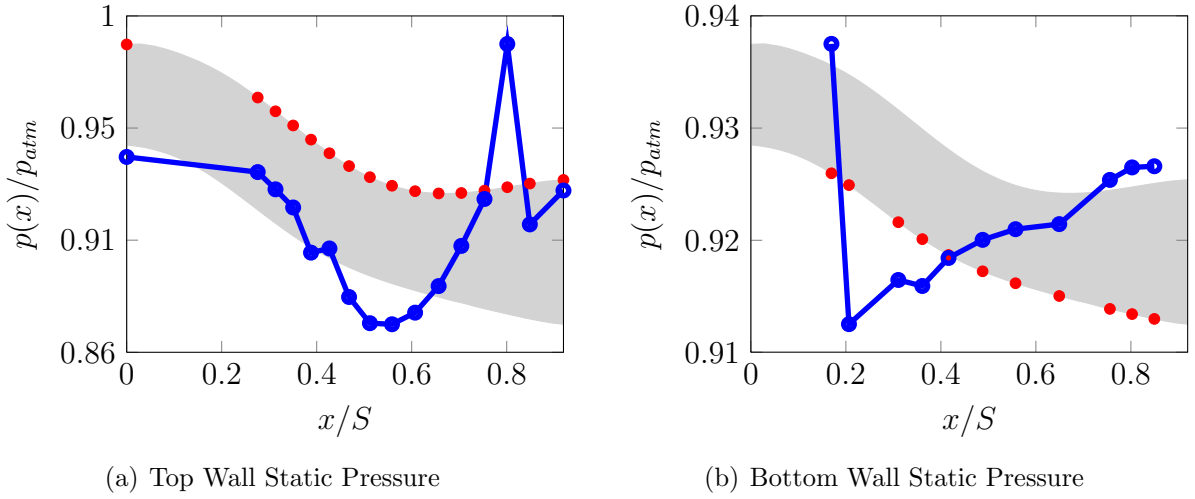


Figure 26: Centerline Streamwise Static Pressure Distribution

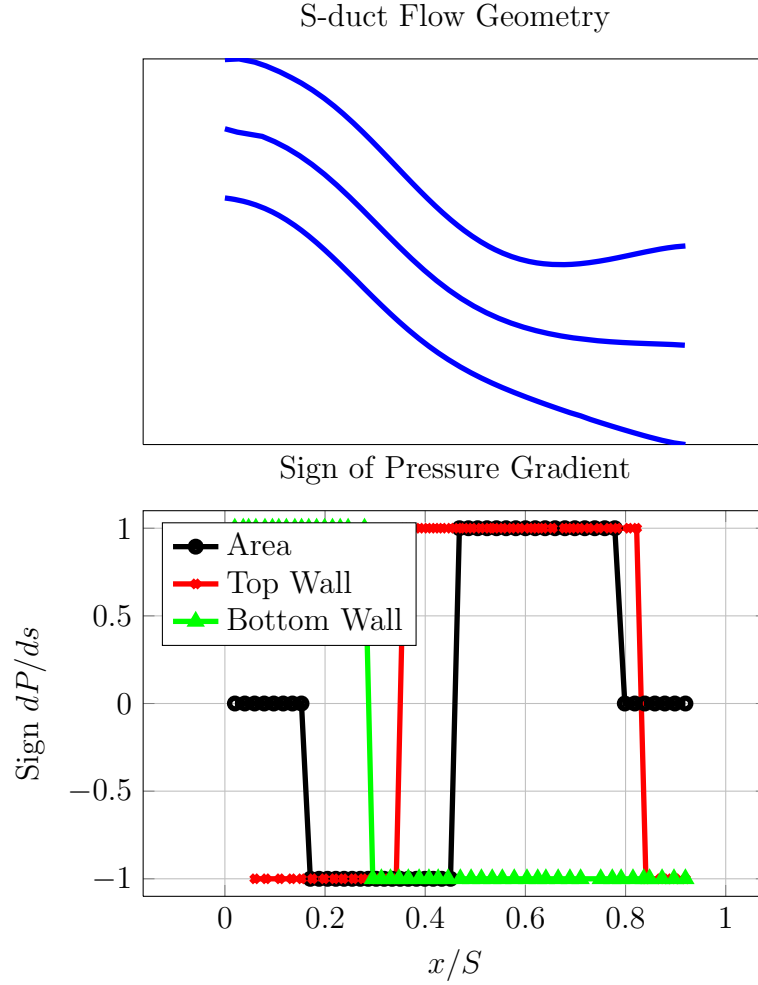
attached around the curve.

Apart from separation and local losses, the development of the total pressure field within the duct is of primary concern for the formation of the exit velocity profile. The transport of the non-uniform wake flow that is ingested by the inlet is largely responsible for the distorted flow pattern that leaves the S-duct and enters the engine at the AIP. The transport is driven by static pressure, shape, separation, and viscous effects. The separation bubbles that form due to adverse gradients behave as flow blockages, forcing the remaining air to flow through a smaller area. In addition, as the flow passes a separated region, available energy is removed and dissipated through viscous losses. These losses reduce the overall total pressure ratio of the inlet and increase distortion.

The final factor affecting the transport of the non-uniform flow through the duct is the flow area shape change. As shown in Figure 16 the throat of the duct is similar to a half-circle shape as would be typical for an airframe/inlet interface. Through the flow path of the duct, the cross-sectional shape transitions from a semicircular shape to a full circle at the AIP. Defining a compactness ratio as in Equation 5.4, this shape change can be investigated. As the cross-section of the duct approaches a circle, the compactness ratio approaches unity.

$$C = \frac{\text{Flow Area}}{\text{Area of a circle with the same perimeter as the flow area}} \quad (5.4)$$

As shown in Figure 28, the duct used in this study rapidly transitions to a circular cross-section near the AIP. This delayed transition causes the total pressure deficit region that entered the duct at the inlet throat to remain near the bottom of the duct through the AIP plane [15]. Shifting the transition upstream could have the effect of smearing the low-pressure region about the circumference. The adjustment to the total pressure profile would

**Figure 27:** Expected Sign of Static Pressure Gradient

have implications at the AIP in two ways: (1) the extent of the distorted region at the AIP would likely increase and (2) the intensity of the distorted region at the AIP would decrease based on continuity considerations. The combination of extent and intensity determine the engine response to a distortion pattern [9], and so the internal duct transition design would affect both downstream rotor performance and operability.

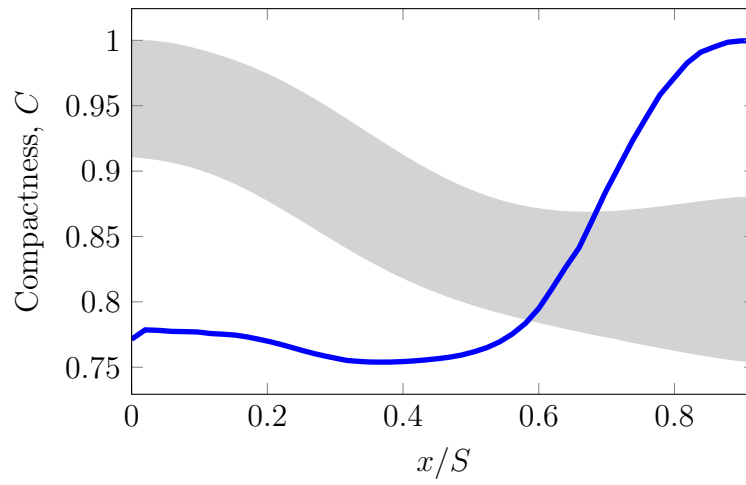


Figure 28: Flow Area Compactness

5.4 Duct Outlet Conditions

The total pressure profile of the flow leaving the duct at the AIP was measured using a 40-probe total pressure rake, designed in the fashion recommended by the Society of Automotive Engineers Recommended Practice ARP1420 [31]. The probe consisted of eight arms, each holding five total pressure probes. As noted above, the total pressure profile leaving the duct is very important because this flow is directly presented to the engine operating behind the S-duct inlet. After the flow has passed the AIP the S-duct has no more ability to shape the flow, and thus the engine must deal with the non-uniformities that exist. Figure 29 displays the total pressure field at the AIP for the lowest and highest flow rates tested. The values of total pressure are normalized by the atmospheric pressure. In this way, the contour plot shows the local total pressure recovery.

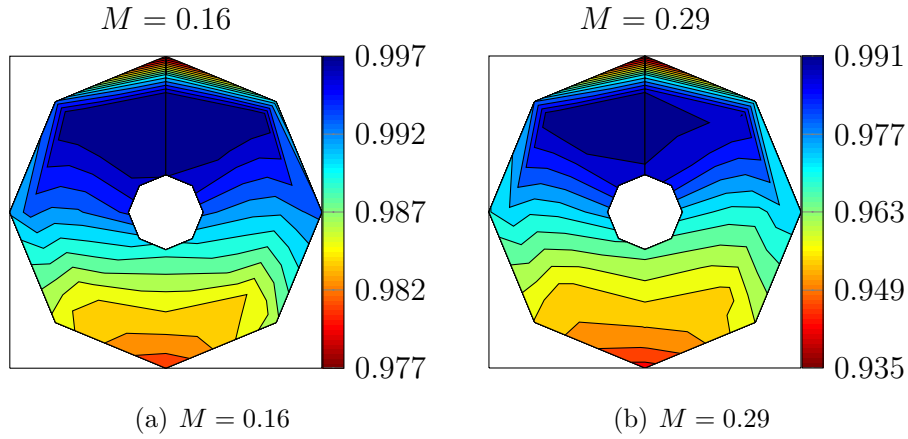


Figure 29: AIP Total Pressure Profiles

The values of pressure recovery represent the performance of the entire inlet/diffuser system. Remembering that this system now consists of both the ingested wake and the S-duct, the values recorded are a characterization of the total pressure loss between the free stream and the engine. Employing Equation 5.1, the overall pressure recovery can be separated into the airframe and S-duct pressure recovery, listed in Table 5. The important result is that the S-duct pressure recovery (from the throat to the AIP) is substantially higher than the overall recovery. The worst S-duct recovery performance is $r_{sduct} = 0.9952$, while the overall recovery was $r_d = 0.9717$. Put simply, the majority of the losses occurred upstream of the S-duct.

The pressure recovery decreases as flow rate is increased. As flow velocity increases, the viscous losses are worsened. Additionally, as noted in Figure 20, the average total pressure entering the S-duct decreased with flow rate and the wake form factor increased (Table 4). The result is a reduced average total pressure entering the duct leading to a lower total pressure at the AIP. In a system installed on an aircraft, the implication is that engine-face

Table 5: AIP Total Pressure Recovery

Free Stream Mach	Throat Recovery $r_{airframe}$	AIP Recovery r_{sduct}	Throat-AIP Recovery $(r_{sduct})(r_{airframe})$
0.16	0.9938	0.9912	0.9974
0.19	0.9911	0.9882	0.9971
0.21	0.9878	0.9845	0.9967
0.24	0.9832	0.9788	0.9955
0.29	0.9764	0.9717	0.9952

total pressure losses will increase with flight speed. This loss would be offset by the increase in propulsion efficiency produced by BLI, as explained by Smith [32]. The optimum design of an S-duct inlet system is therefore a multi-disciplinary problem.

Again referring to Figure 29, the total pressure profiles indicate two regions of low total pressure. The region near the top of the AIP is entirely a result of the separation that occurs on the top wall of the duct near the AIP (Figure 26). The low total pressure region at the bottom of the AIP is a result of the wake profile ingested as well as flow separation along the bottom wall of the duct (Figure 26). The region would have a low total pressure simply due to BLI, but the separation within the S-duct causes a loss that worsens the total pressure deficit.

5.4.1 Effect on Stall Margin (ARP1420), Data Processing Techniques

ARP1420 provides a methodology for the characterization of total pressure distortions. For each case tested, the ARP1420 distortion parameters are computed. The parameters of particular interest to engine response are: Multiple-Per-Rev, Circumferential Intensity, Extent, and Radial Intensity. The Multiple-Per-Rev is a representation of the number of low total pressure regions at the AIP. A blade rotating in the flow will encounter periodic forcing according to the number of reduced total pressure regions. The flow separation near the top of the AIP adds a second low pressure region near the tip of the blades.

Circumferential Distortion Elements

ARP1420 defines distortion elements in the circumferential and radial directions. The circumferential distortion is defined by the intensity, extent, and multiple-per-revolution elements on a given instrumentation ring. These quantities are calculated using a graphical approach. Figure 30 displays a sample plot of the total pressures measured around an instrumentation ring from ARP1420 for a typical one-per-rev distortion pattern. *PAV* represents

the numerical average of the total pressures around the ring, calculated using Equation 5.5. $PAVLOW$ is the average of the total pressures from the locations that fall below PAV , calculated using Equation 5.6.

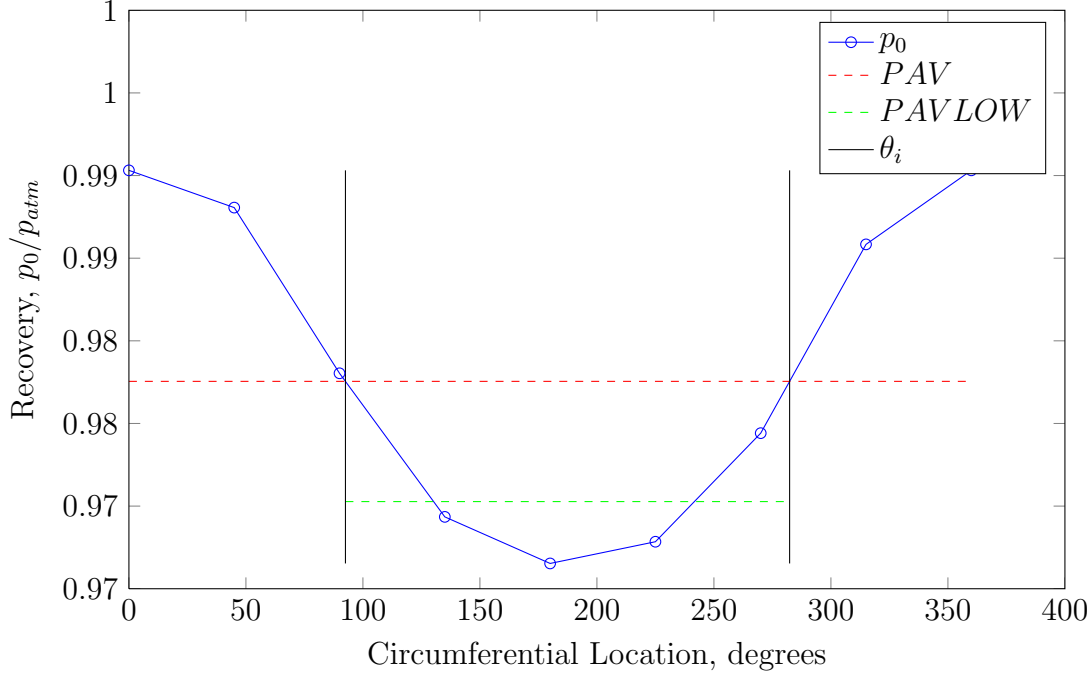


Figure 30: Typical Total Pressure Plot for a Ring with a One-Per-Rev Distortion

The extent (θ_i^-) characterizes the size of the low-pressure region and is calculated as shown in Equation 5.7, by taking the difference between the circumferential locations at which the linearly interpolated plot of total pressures around the ring crosses the average pressure, PAV . The intensity ($\Delta p_c/p$) is a numerical descriptor of the magnitude of the pressure distortion and is calculated using Equation 5.8. The multiple-per-revolution element quantifies the number of effective low pressure regions around a given instrumentation ring that fall below PAV .

$$PAV = \frac{1}{360} \int_0^{360} p(\theta) d\theta \quad (5.5)$$

$$PAVLOW = \frac{1}{\theta_i^-} \int_{\theta_{1_i}}^{\theta_{2_i}} p(\theta) d\theta \quad (5.6)$$

$$\theta_i^- = \theta_{2_i} - \theta_{1_i} \quad (5.7)$$

$$\left(\frac{\Delta p_c}{p}\right) = \left(\frac{PAV - PAV_{LOW}}{PAV}\right) \quad (5.8)$$

If a ring has multiple low-pressure regions separated by less than 25 degrees, it is treated as an equivalent one-per-revolution region. However, if multiple low pressure regions are separated by more than 25 degrees, the intensity is taken as the intensity for the region corresponding to the maximum value of Expression 5.9.

$$\left(\frac{\Delta p_c}{p}\right) \theta_i^- \quad (5.9)$$

The extent is then taken as the extent of this same region. The combined effects of intensity and extent strongly influence engine performance. The fundamental reason is that a rotating blade requires time to respond to a distortion. If the intensity and extent do not influence the blade strongly for a sufficient period of time, the fan response can be minimal.

Radial Distortion Elements

The radial distortion intensity $(\Delta p_r/p)_i$ describes the difference between the ring average pressure and the face average pressure for each instrumented ring. Using Equation 5.10, the radial distortion intensity was also calculated.

$$\left(\frac{\Delta p_r}{p}\right)_i = \frac{PFAV - PAV}{PFAV} \quad (5.10)$$

The face average pressure, $PFAV$ can be calculated using Equation 5.11.

$$PFAV = \frac{1}{N} \sum_{i=1}^N PAV_i \quad (5.11)$$

The focus of ARP1420 is on the effects of distorted flow on fan stall margin. The methods do not relate to other aspects of engine performance, but deal with the changes to stability pressure ratio ΔPRS caused by non-uniform AIP flow. Equation 5.12 relates the circumferential distortion intensity $(\Delta p_c/p)_i$ and radial distortion intensity $(\Delta p_r/p)_i$ to loss in stability pressure ratio or stall margin.

$$\Delta PRS = 100 \sum_{i=1}^N \left[KC_i \left(\frac{\Delta p_c}{p}\right)_i + KR_i \left(\frac{\Delta p_r}{p}\right)_i + C_i \right] \quad (5.12)$$

The constants KC_i , KR_i , and C_i depend on the design of the fan or compressor, which was not part of this study. Thus, values for ΔPRS are not available. However, reduction in ΔPRS will result in an improved stall margin. Reductions in $(\Delta p_c/p)$ and $(\Delta p_r/p)$ will result in a lower ΔPRS , and therefore improve the stall margin of the engine-BLI inlet system. The flow control had the effect of reducing $(\Delta p_c/p)$ significantly, which would improve stall margin. These results are presented in Section 7.4.1.

5.4.2 Total Pressure Distortion (ARP1420) Results

Unwrapping the total pressure profile and plotting it by rings shows the severity of the distortion clearly. Figure 31 shows such a plot for the high speed case ($M = 0.29$). Ring 1 is near the center of the AIP, and Ring 5 is near the outer wall.

Each trough in the total pressure around a ring represents a low total pressure region. The crossing of the total pressure measurement with the ring-average total pressure defines a distorted region. The crossing points define the extent, and the depth of the trough relates to the intensity.

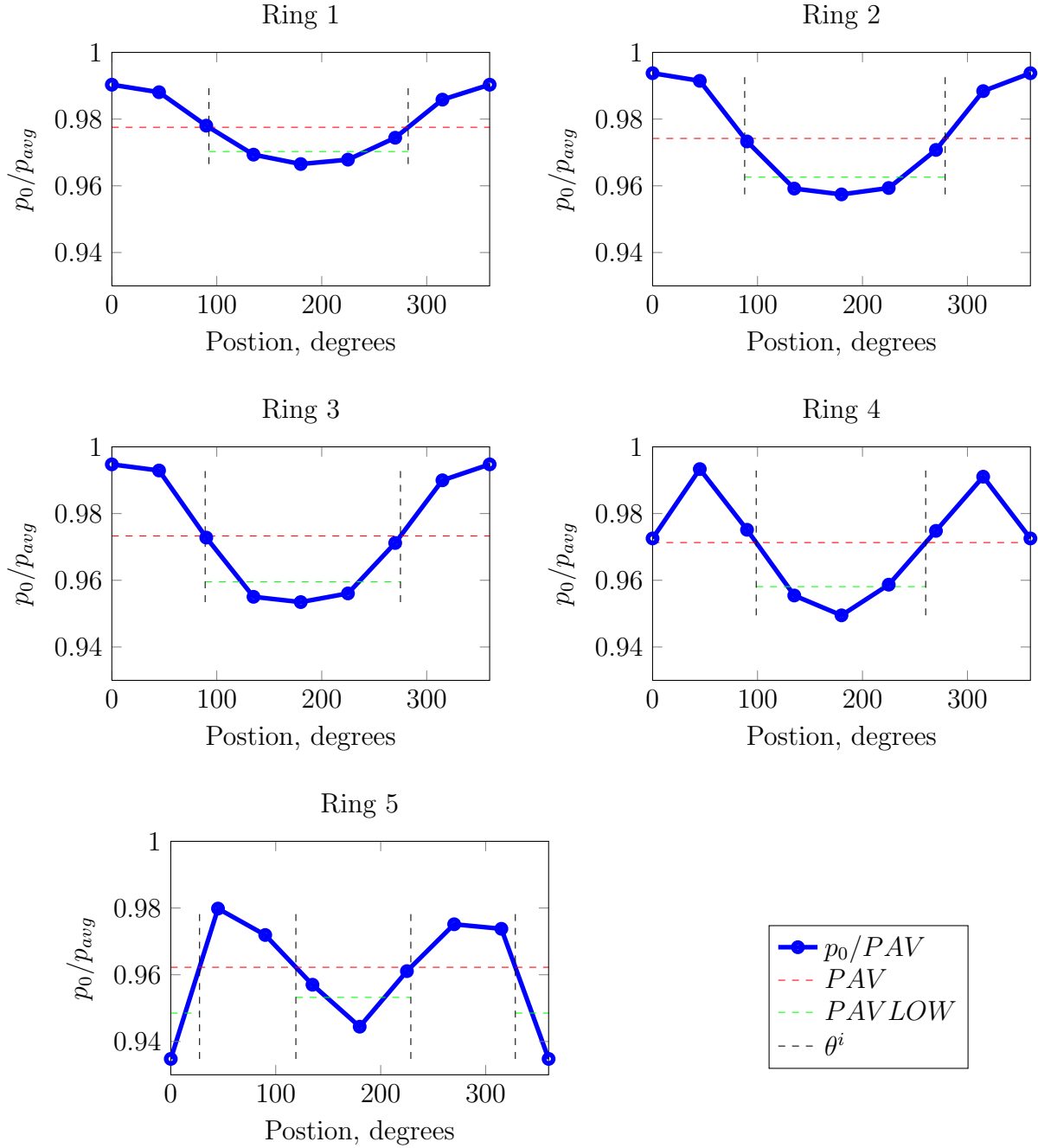
The extent of the distortion region is a measure of the angle swept out of the AIP plane. Inspection of the distorted region near the bottom of the AIP shows that the extent did not vary greatly with flow rate, since the shape (thickness) of the wake did not change much as flow rate increased.

The total pressure deficit increased dramatically in the ingested wake as flow rate increased. Thus, the intensity of the distortion at the AIP also increased. Additionally, the separation near the bottom wall reduced the total pressure further. Figure 32 plots the distortion intensity for the region centered at the bottom of the AIP for each ring against flow speed.

Inspection of the distorted region near the top of the AIP leads to further insight into the effects of separation within serpentine inlets. Figure 33 shows a plot of the extent of the separated region for each flow rate.

The plot of Figure 33 indicates that the separation occurred at all flow rates tested because a distorted region existed at the top of the duct (marked by a non-zero extent). This observation confirms the fact that a separation actually occurred, as both the static pressure plots and the AIP total pressure plot indicate its presence. Interestingly, the size of the separation bubble at the AIP decreased as flow rate increased. At the lowest speed, the bubble was large enough to affect Ring 4 as well as Ring 5. As the speed increased, the separation no longer reached far enough into the flow to affect Ring 4.

With increased velocity the flow can withstand a larger adverse static pressure gradient, and separation is delayed. The result is that the separation occurs slightly farther downstream in the duct, and its effects do not propagate as far into the flow. Additionally, moving away from the top centerline of the duct, the curvature was less severe. The adverse static pressure gradient was slightly reduced, and separation occurred farther downstream. As flow speed

**Figure 31:** AIP Total Pressures By Ring

increased, this effect was amplified, and the Ring 5 extent decreased. Figure 34 shows a schematic of the separation front about the top centerline of the duct. Flow is from bottom to top of the image. The wider curve represents the approximate separation front for the low speed case, and the narrower curve represents the approximate separation front for the

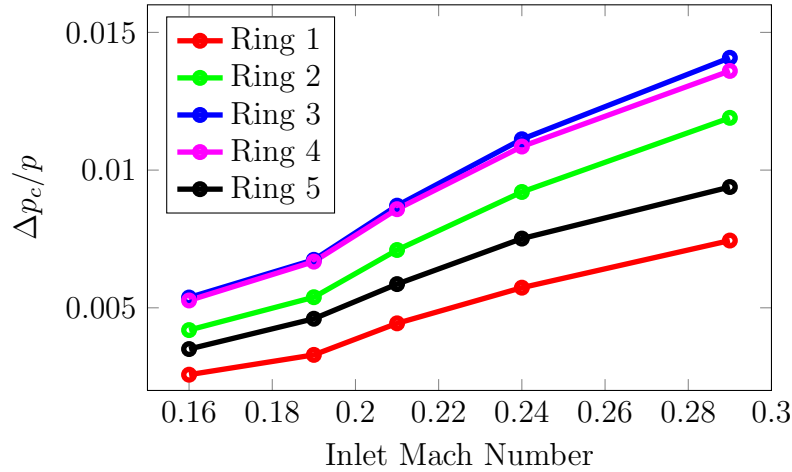


Figure 32: Circumferential p_0 Distortion Intensity versus Free Stream Mach Number

high speed case.

The intensity of the separated region increased with flow speed. The total pressure in a separation bubble is close to the static pressure. As flow speed increases, the static pressure decreases while the total pressure remains constant (apart from losses). Combining these effects, the total pressure deficit in a separated region increases with flow speed, as shown in Figure 35.

For a multiple-per-rev distortion pattern, such as those observed in this study, ARP1420 provides a method for determining the dominant distortion region, which will have the greatest impact on rotor response. The dominant region is selected based on the combined value of intensity and extent. Cousins [9] shows that rotor response to a flow distortion depends on both intensity and extent. A high-intensity distortion with low extent does not affect the rotor as strongly because the rotor blade spends little time in the region. In all flow speeds tested, the dominant region for Ring 5 is the top region that was caused by separation. The result is that a small separation bubble near the AIP can have a greater impact on engine response than the full effect of wake ingestion and separation along the bottom surface farther upstream. Thus, designing S-ducts to avoid separation near the AIP is of great importance both to total pressure recovery and engine response.

The final observation is that ARP1420 provides a methodology for characterizing total pressure distortions and correlating engine stall/surge limits. In this way, an engine and inlet can be matched for stability using the distortion parameters. The other aspect of engine response to non-uniform inlet flow of interest is performance. The performance of the engine relates to the velocity field approaching the rotor, and the variation in velocity and angles of attack associated with distorted regions at the AIP. These variations in velocity and angles of attack change the flow over the rotating airfoils and can lead to separation, causing reduced turning (work addition to the flow), and reduced efficiency (due to increased losses). Complete analysis of the inlet velocity field coming to an engine from a serpentine inlet is

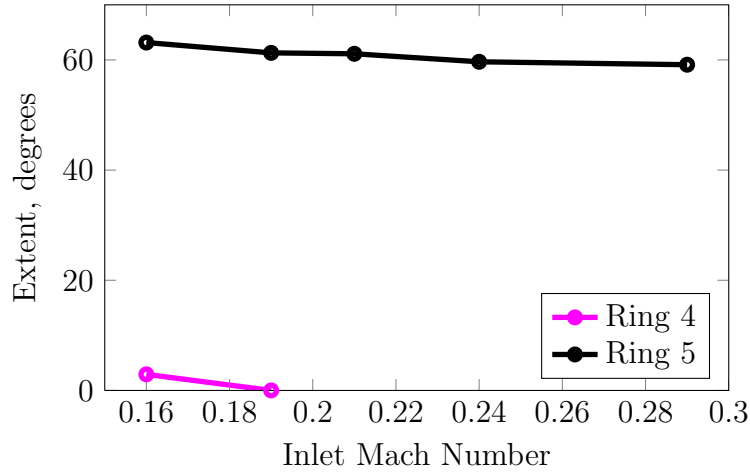


Figure 33: Circumferential p_0 Distortion Extent of Top (Separated) Region versus Free Stream Mach Number

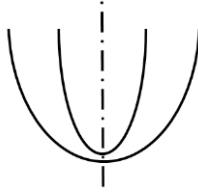


Figure 34: Schematic of the Separation Front about the top centerline of the duct

therefore important to understanding the environment in which the engine must operate and predicting the system performance. The rake used in this study consisted only of axial total pressure measurements. Without the static pressure and velocity vector variations the flow field cannot be accurately computed. A recommendation for future work is to employ measurement instruments capable of determining both axial and swirl velocities in addition to total pressure variations at the AIP.

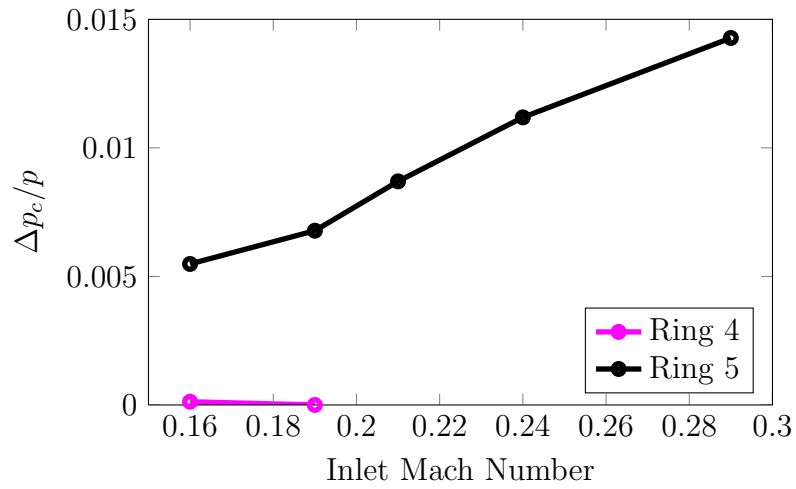


Figure 35: Circumferential P_0 Distortion Intensity of Top (Separated) Region versus Free Stream Mach Number

Chapter 6

Experimental Methods - Flow Control

The primary focus of this test configuration was assessment of the effects of flow rate and bleed control on AIP total pressure distortions. Engine performance in this configuration allowed for testing over an inlet Mach number range of 0.20-0.43, as previously noted in Table 3. In addition to the 40 total pressures measured at the AIP (Chapter 3), measurements were taken of the flow at the inlet throat and bypass duct. The inlet throat was instrumented with a centerline boundary layer total pressure rake consisting of 10 total pressures, and flow symmetry was evaluated using two rakes of 4 probes each offset from the centerline of the inlet throat. The static pressure at the inlet throat was measured at the bottom centerline just behind the S-duct lip at the total pressure measurement plane. Nine total pressure probes and a static pressure tap at the top of centerline measured the flow through the bypass. Eight S-duct wall static pressures measurements provided data for use in comparing the internal flow with CFD modeling. This instrumentation scheme is shown schematically in Figure 36. The details of the measurement system and an uncertainty analysis are presented in Appendix A.

6.1 Measurements of Serpentine Inlet Performance

The ingested boundary layer flow entering the serpentine inlet was measured using a centerline 10-probe total pressure rake along with a static pressure measurement taken at the bottom centerline wall. This rake provided detail about the boundary layer shape and thickness, as well as the maximum Mach number of the entering flow. This maximum Mach number corresponds to the free stream velocity, or the simulated flight speed of the wind tunnel. In order to measure the symmetry of the flow two additional total pressure rakes of 4 probes each were stationed to either side of the 10-probe boundary layer rake, dividing the throat plane into four sections, as shown in the photograph of Figure 37.

Three rakes with three total pressure probes each were situated at the centerline and to either side in the entrance plane of the bypass duct. Figure 38 provides a picture of the

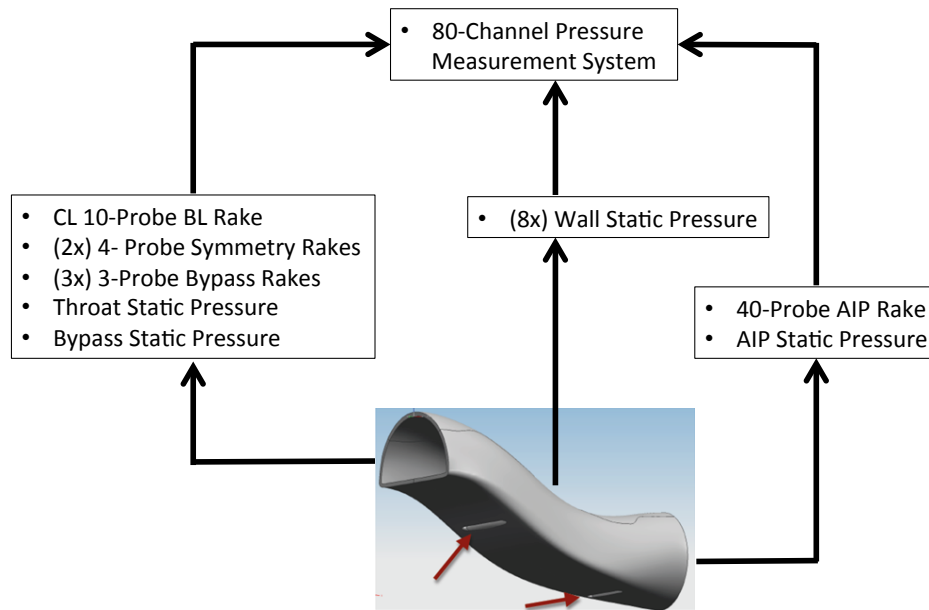


Figure 36: Flow Control Experimental Configuration Schematic

probe installation. These probes were able to measure the maximum Mach number of the bypass flow, which matched the maximum Mach number of the throat flow. The rakes positioned to either side of the centerline enabled confirmation of the flow symmetry during the experiment. The bypass rakes also enabled an estimate of the mass flow split between the BLI serpentine inlet and the bypass duct at each test condition.

The measurement location of primary interest for this research was the exit of the BLI inlet, designated the Aerodynamic Interface Plane (AIP). The flow pattern at this plane would enter the fan or compressor of an embedded engine. Any distortion to the flow at the AIP is of concern for the reasons previously discussed. The detailed understanding of the flow patterns and distortion at the AIP, as well as the effects of flow control techniques on the distortion, are the principal interest of this study.

6.2 Active Flow Control System Concept and Design

CFD Modeling of the UTRC duct [15] indicated two substantial separation zones, one on the bottom of the first bend and one on the top of the second. In these locations the duct wall curves away from the main flow, forcing the local air to accelerate around the bend. The separation front along the bottom of the inlet was identified as a proper location for bleed flow control to prevent separation. Additionally, a second bleed slot was added near the aft end of the duct to remove boundary layer air and maintain flow attachment. Research was performed with varying quantities of bleed flow through the two slots.



Figure 37: 10-Probe Centerline Boundary Layer Rake and Side 4-Probe Rakes



Figure 38: 3-Probe Bypass Total Pressure Rakes

The bleed control system was designed to consume no more than 2% of the main S-duct flow in steady operation. The function of the bleed system was to remove the low energy air near the bottom of the BLI duct caused by ingestion of the airframe boundary layer and prevent separation. The uniformity of the flow profile at the AIP was improved. A vacuum system, shown schematically in Figure 39, was designed and constructed to provide the desired flows.

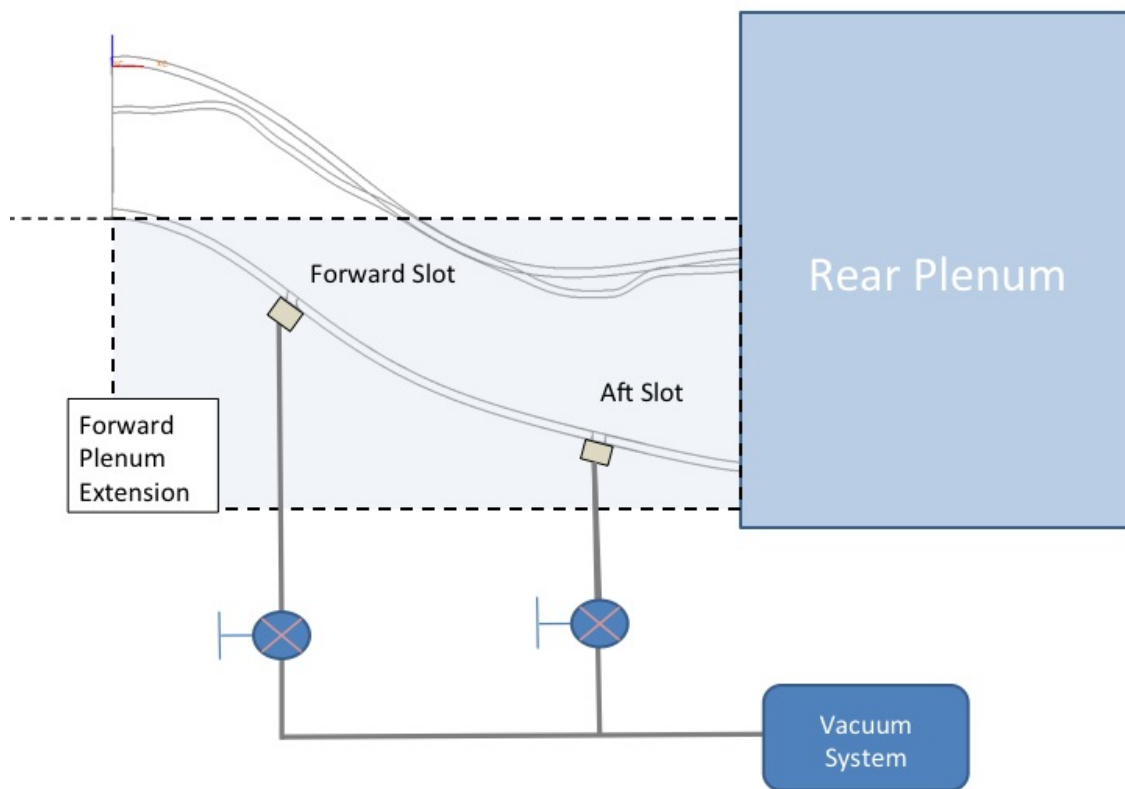


Figure 39: Schematic of Bleed Vacuum System

Chapter 7

Results - Flow Control

7.1 Flow Control Experimental Results

The UTRC BLI inlet incorporating an active bleed control system was tested in a series of experiments at the Virginia Tech wind tunnel following the methods of Chapters 3 and 6. First, the flow through the serpentine inlet was measured without flow control for a range of inlet Mach numbers from 0.2 to 0.43. The results from these tests were used as a baseline comparison for testing the effectiveness of the bleed flow control. Additionally, the effect of the flow rate through the duct on the AIP flow profiles was determined. The bleed control experiments were performed using control flows ranging from 0% to approximately 2% of the total inlet flowrate for the same range of inlet Mach numbers.

7.2 Experimental Environment

The UTRC S-duct was tested for a range of approach flow velocities, as discussed above. At each inlet flow speed, the boundary layer entering the serpentine inlet was measured. The profiles generated by this data were used to determine the approach Mach number as well as the boundary layer thickness. As summarized previously in Table 3, the boundary layer thickness ranged up to 52% of the inlet height, and the approach Mach number varied from 0.2 to 0.43. The profiles in Figure 40 indicate the shape, thickness, and pressure recovery for each flow case. The flow control employed within the duct to reduce AIP distortions had little effect on the boundary layer ingested by the BLI inlet.

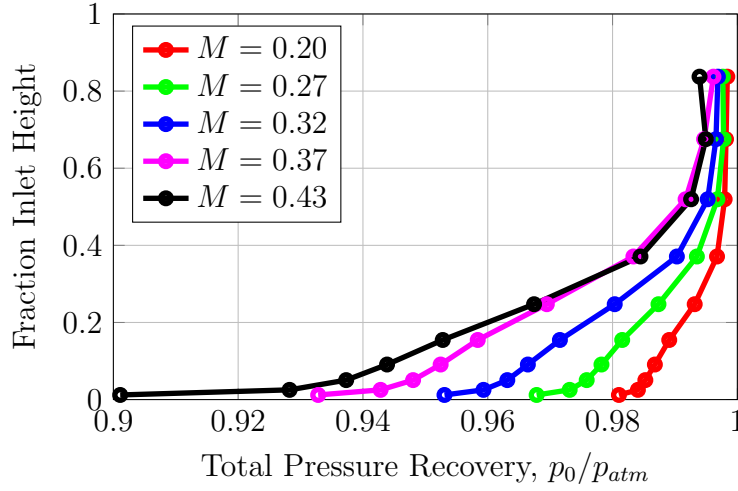


Figure 40: Throat Pressure Recovery at Each Condition Tested

7.3 Effects of Flow Control

This section presents the results of the bleed flow control experiments. The goal of the flow control employed in this study was to remove the low-pressure air caused by the ingestion of the boundary layer and induce high-pressure airflow to fill in the gap. Thus, the flow control should cause the graphs of total pressure around each ring to flatten and move toward a uniform value across all rings.

Bleed flow control removed the low-speed flow that resulted from the ingestion of the boundary layer. Cases were tested for inlet Mach numbers ranging from 0.2 to 0.43. At each inlet flow speed, the bleed system was used to remove no more than 2% of the total mass flow through the BLI inlet. Two bleed ports were employed, one at the forward end of the inlet and one at the aft near the AIP, as shown in Fig. 5. The location of these bleed ports was chosen based on the separation fronts observed in UTRC CFD modeling. Approximately 1.4% of the total mass flow through the S-duct was removed through the forward bleed port, and approximately 0.5% of the total mass flow was removed from the aft port. Presented in this section are the cases for the lowest and highest inlet Mach numbers. The intermediate cases were used to generate the plots in the section of this report that discusses effects on stall margin.

7.3.1 Inlet $M = 0.2$

The regions of interest are those that drop below PAV in the plots of Figure 31 (Chapter 5). The goal of the flow control was to reduce the magnitude of the deficit of these regions, resulting in a more uniform flow field at the AIP. Figure 41 shows the Ring 4 and Ring 5 plots for an inlet $M = 0.2$, with varying flow control as a sample. The three control cases

tested with the bleed quantities discussed above were no bleed, forward bleed, and forward and aft bleed. As shown in Figure 41, the effect of the bleed was to reduce the magnitude of the total pressure deficit, primarily in the region centered about the $\theta = 180^\circ$ location at the AIP. For AIP instrumentation Rings 1-4 (counting outwardly starting with the innermost ring), the removal of the boundary layer as it entered the BLI inlet (forward suction) resulted in a significant improvement of the total pressure profiles. For the outer ring (Ring 5), the aft suction produced a larger effect than the forward suction. This is because the addition of aft suction was able to further mitigate the effects of the boundary layer ingestion, including the development of that flow through the inlet.

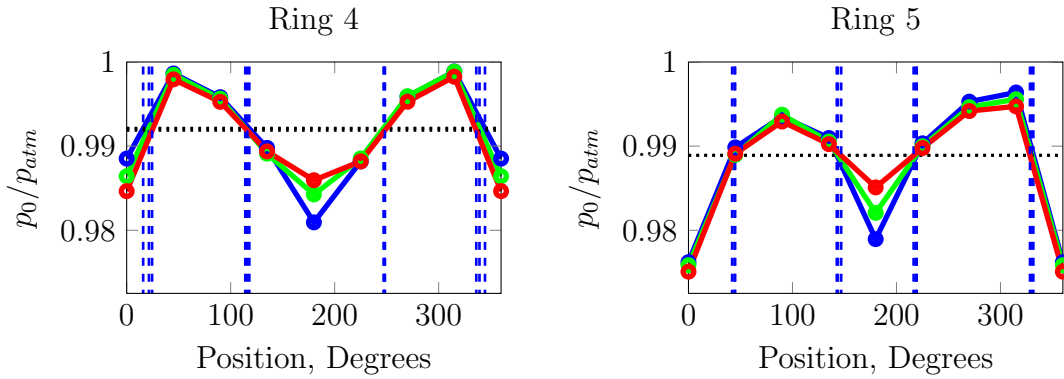


Figure 41: AIP Total Pressures with Flow Control at 2% S-duct Mass Flow at $M = 0.2$

The polar plots of Figure 42 give a qualitative indication of the effect of flow control on the AIP flow profile. As the bleed flow was brought online, first at the forward slot and then at the aft slot, the low total pressure region centered at the 180° AIP location was greatly reduced. This contraction of the low-speed region indicated that the bleed system successfully removed the low-speed air, giving way to high-speed flow and a more uniform AIP flow profile.

The $M=0.2$ flow-controlled AIP profile data plotted in Figure 42 suggest that larger bleed quantities would further reduce the low total pressure region at the bottom of the AIP. However, a trade-off exists between removing distorted flow and reducing the effectiveness of the turbomachine by limiting the flow it receives. Additionally, work is required to bleed the flow, and an increase in bleed results in a greater control system power demand. This power requirement may reduce the system level performance of the embedded engine. The effects of distorted flow on engine performance must first be determined before an optimal bleed system design can be realized. Further research related to the distortion effects on engine performance is required.

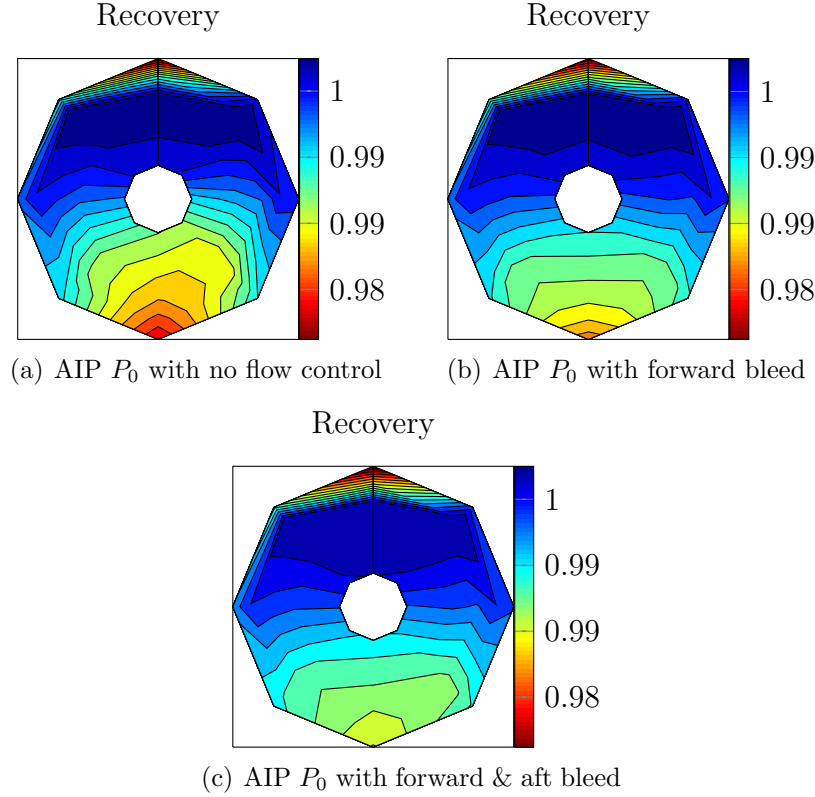


Figure 42: AIP Total Pressure Contours for no Flow Control Cases at $M = 0.2$

7.3.2 Inlet $M = 0.43$

The results for the highest inlet flow speed tested followed the same trends as for the cases with the inlet $M = 0.2$. However, the bleed system was not capable of producing the desired 1.4% bleed from the forward slot. The forward slot bleed was reduced to 1% of the total mass flow through the BLI inlet. Thus, the trends in total pressures shown in Figure 43 were similar, but the overall effectiveness was reduced. Expansion of the bleed system capacity would allow future tests at the desired bleed flow quantities to be conducted.

The polar plots shown in Figure 43 again show a significant improvement in the AIP flow distribution. The low-pressure region centered at $\theta = 180^\circ$ within the AIP contracted as the bleed systems were employed. Greater improvements can be expected with increased quantities of bleed flow.

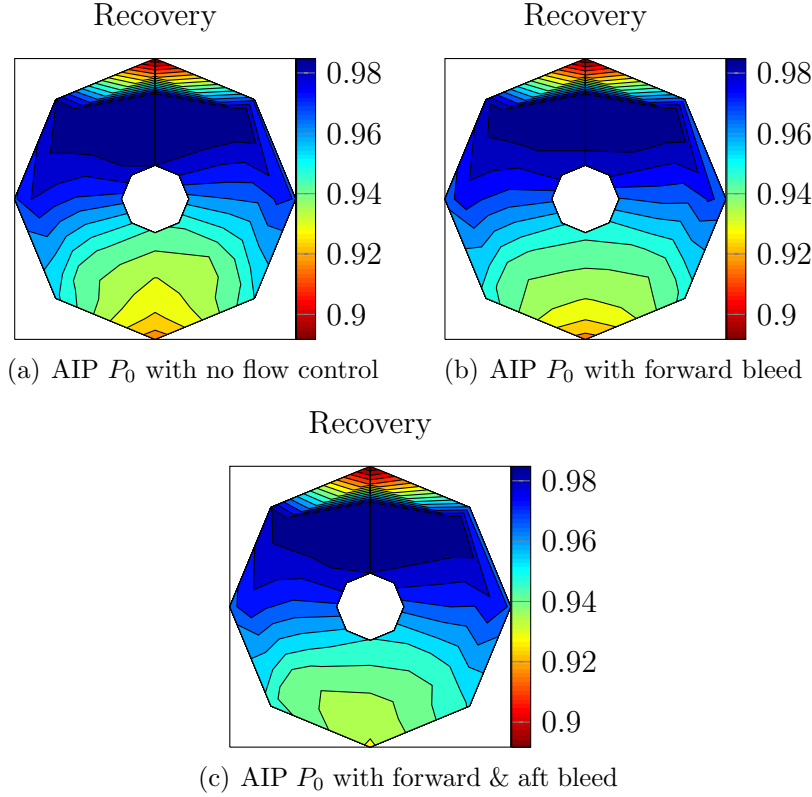


Figure 43: AIP Total Pressure Contours for no Flow Control Cases at $M = 0.43$

7.4 Effect on Stall Margin (ARP1420), Results

ARP1420 provides guidelines to assess the effect of inlet distortions on fan and compressor stall margin. It is considered useful to reduce the measured data following the methods prescribed in ARP1420, to provide additional insight into the effect of the flow control in the duct. The primary interest of this study was the flow pattern at the AIP. Specifically, the interest was to determine the AIP distortion intensity as defined by ARP1420 and quantify the effects of active bleed flow control on this intensity.

7.4.1 Effects of Flow Control on Distortion Intensity

As can be seen from the polar plots in Figures 42 and 43, the distortion region centered about the 180 degree location at the AIP was reduced by the application of bleed flow control. For cases with inlet Mach numbers ranging from 0.2 to 0.43 and bleed flow control, the distortion parameters of ARP1420 were calculated. The flow control reduced the circumferential distortion intensity for all rings while leaving the circumferential distortion extent relatively unchanged. This result is consistent with the observations above. Figure 44 provides plots

of the distortion intensity ($(\Delta p_c/p)$) for both the uncontrolled and controlled cases at the $\theta = 180^\circ$ location. Similarly, Figure 45 plots the distortion intensity for the $\theta = 0^\circ$ location. As the inlet Mach number increased, the circumferential distortion intensity increased. The flow control mitigated this effect by reducing the circumferential distortion intensity of the $\theta = 180^\circ$ region, while a slight adverse affect was observed at the $\theta = 0^\circ$ location. The growth of $(\Delta p_c/p)$ in the $\theta = 180^\circ$ region was slowed by the application of bleed flow control.

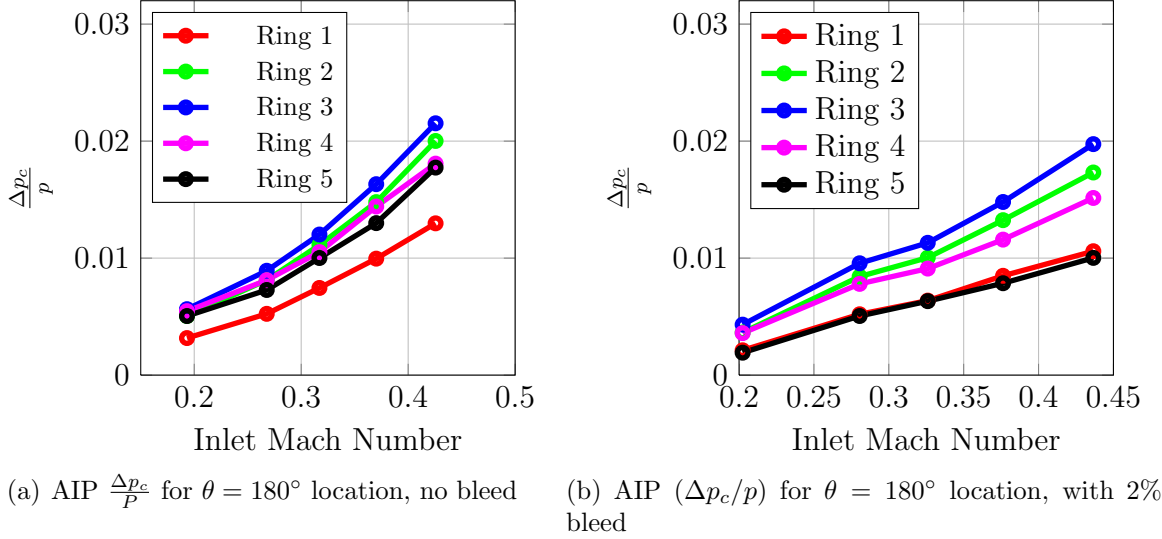


Figure 44: AIP Circumferential Distortion Intensity versus Inlet Mach Number, $\theta = 180^\circ$ location

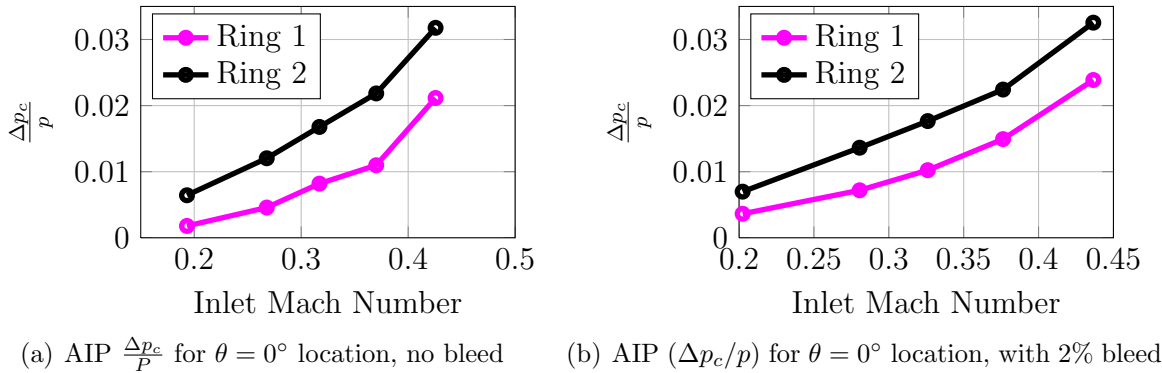


Figure 45: AIP Circumferential Distortion Intensity versus Inlet Mach Number, $\theta = 0^\circ$ location

To determine the effect of flow control on distortion intensity, the two bleed ports were activated one at a time. For the lower and upper limiting cases of inlet $M = 0.2$ and 0.43 , plots were generated to show the trend in circumferential distortion intensity in each ring as the flow control was enabled. Figure 47 shows these representative trends. In both cases, the

forward suction of approximately 1.4% of the total mass flow through the duct reduced the circumferential distortion at the $\theta = 180^\circ$ location. In the $M = 0.2$ case, the ring-averaged distortion intensity was reduced by 22%. The additional bleed from the aft suction port of approximately 0.5% of the total flow added to this effect, reducing the average distortion intensity by a total of 36% relative to the uncontrolled case. For the $M = 0.43$ case, forward suction reduced the distortion intensity by an average of 5%. With forward and aft bleed, the ring-averaged distortion intensity was reduced a total of 19%. During the experiment, for the $M = 0.43$ case, the vacuum system's maximum capacity was reached. The total bleed flow was limited to 1.6% instead of the desired 2% of total mass flow through the BLI inlet. Based on the $M = 0.2$ data, expansion of the bleed suction system to yield the desired 2% bleed flow would be expected to demonstrate further reduction in distortion intensity. Figure 46 provides a plot of these trends.

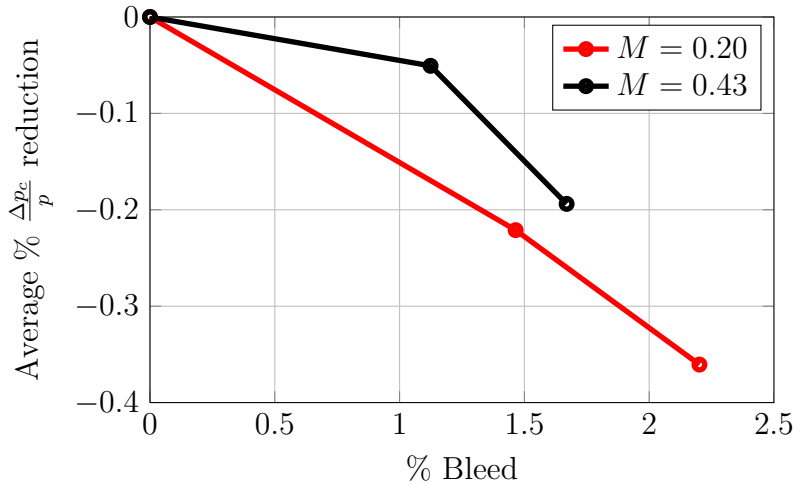


Figure 46: % Reduction in AIP Circumferential Distortion Intensity ($\Delta p_c/p$) for bleed flow control

A reduction in $(\Delta p_c/p)$ would be expected to result in an improved stall margin, according to Equation 5.12. Although the constants necessary to evaluate ΔPRS are unavailable, a reduction in the $(\Delta p_c/p)$ term will result in a reduced stability pressure ratio loss due to distortion. Thus, a reduction in the ring-averaged $(\Delta p_c/p)$ gives an indication of improvement or worsening of the stability pressure ratio. Figure 46 shows the declining trend in the $\Sigma(\Delta p_c/p)$ for each inlet Mach number as bleed flow control is employed. The flow control improved the stability pressure ratio, or the stall margin of a downstream embedded engine.

7.4.2 Special Observations for the $\theta = 0^\circ$ Location

The distortion intensity at the $\theta = 0^\circ$ location followed an increasing trend with bleed applied to the bottom wall. The distortion in this region resulted from a separation occurring in the

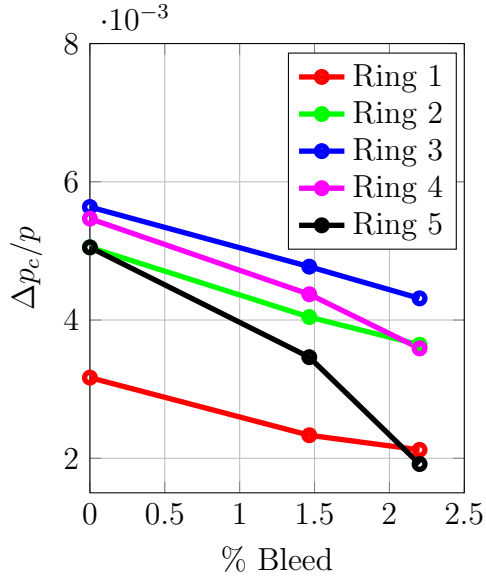
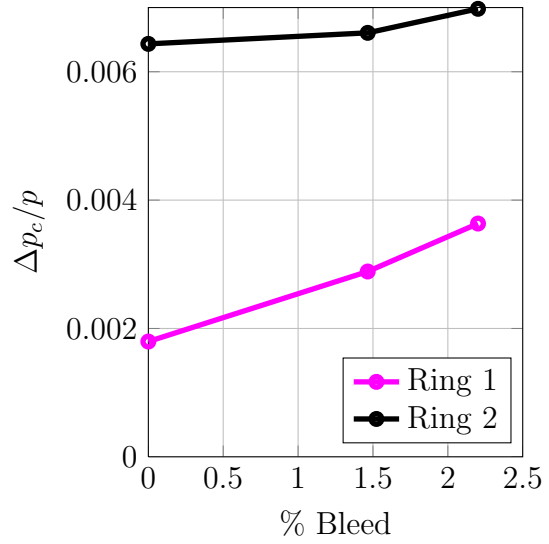
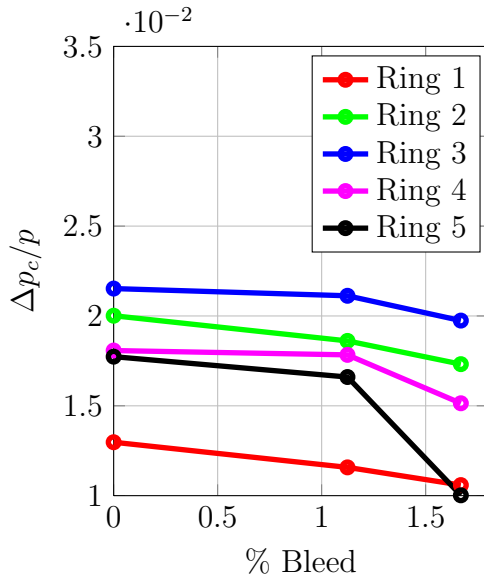
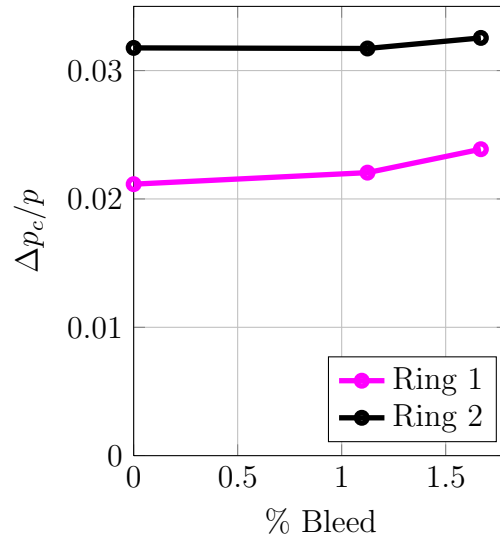

 (a) $M = 0.2$ Case, for $\theta = 180^\circ$ location

 (b) $M = 0.2$ Case, for $\theta = 0^\circ$ location

 (c) $M = 0.43$ Case, for $\theta = 180^\circ$ location

 (d) $M = 0.43$ Case, for $\theta = 0^\circ$ location

Figure 47: AIP Circumferential Distortion Intensity versus Bleed Flow Rate

second bend of the S-duct. This separation bubble was pulled down by the application of the flow control, causing its intensity to increase slightly (3%) as shown in the right-hand plots of Figure 47. As noted in Section 5.4.2, the dominant distortion region affecting fan stall margin is located in this separation bubble at the $\theta = 0^\circ$ AIP location.

The bleed flow control had a positive effect on the distortion region centered at the $\theta =$

180° location AIP location. Although this effect did not improve stall margin according to ARP1420 methodology, it will influence the performance of an engine. All distortion regions measured at the AIP will have an effect on compressor efficiency and engine performance. A reduction of any distortion region will improve the performance of the engine, and is valuable for that reason. The bleed flow control reduced the circumferential distortion intensity for the Ring 5 region centered at the 180 degree AIP location by as much as 43% at the highest Mach number test case. This significant reduction in Ring 5 circumferential distortion will improve engine performance, regardless of its effect on stability pressure ratio.

7.5 Agreement between Experimental Results and UTRC Modeling

The circumferential distortion intensity results from the experiments performed at Virginia Tech were compared to the results obtained from the UTRC modeling for the uncontrolled cases. The modeling was performed at an inlet Mach number of 0.35, which was not one of the inlet Mach numbers tested. However, as can be seen by the curves in Figure 48, the trends in the data matched well. This agreement between numerical and experimental results supports the accuracy of the UTRC modeling methods.

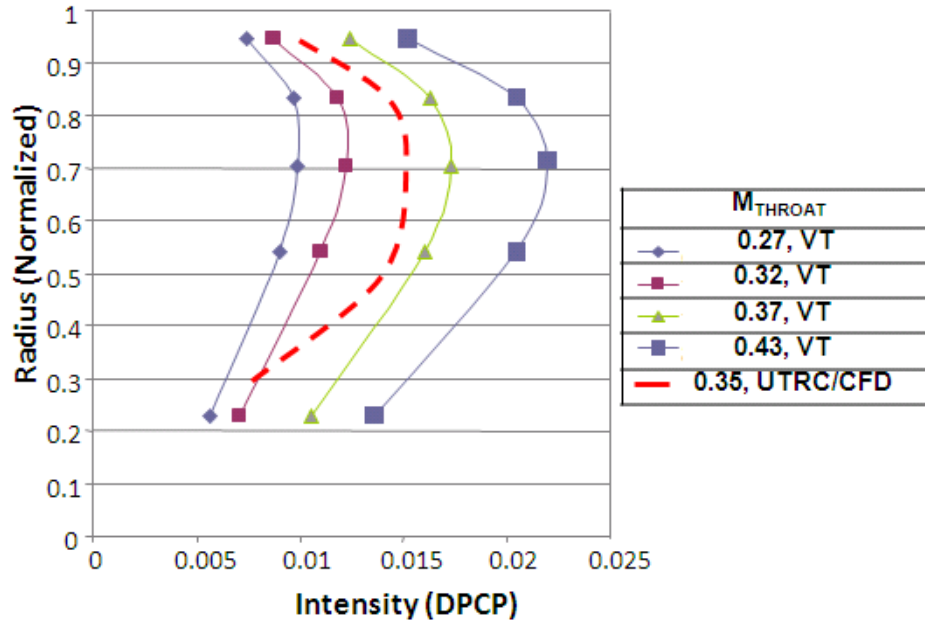


Figure 48: Comparison of Experimental Results and UTRC Modeling Predictions

Chapter 8

Discussion of Results

8.1 Introduction

Following a development similar to the structure of Chapter 2, the overall results of this study are briefly summarized and discussed in this section. First, the benefits of a boundary layer ingesting embedded engine based on the analysis presented and utilizing the UTRC S-duct are discussed. Next, the flow behaviors related to the serpentine inlet are presented. Finally, a discussion related to the benefits and cost of flow control is presented.

8.2 Benefits of a BLI Embedded Engine

An embedded engine offers performance improvements in the areas of noise, emissions, observability, and fuel consumption. The impact of the specific duct studied on these system metrics is beyond the scope of the study and the measurements made in the experiments presented herein. However, some information related to the fuel consumption improvement related to the BLI embedded engine system is available.

The fuel burn (and therefore emissions) of an airplane utilizing this serpentine inlet could be significantly improved. The nacelle drag is substantially reduced by the high degree of offset and compactness of this duct design. Additionally, inlet diffusion drag (force required to decelerate the inlet air from flight speed to an acceptable engine face speed) reductions can be expected because the momentum of the flow entering the inlet is less than free stream. The viscous effects over the simulated airframe reduce the momentum of the inlet air, producing a thick ingested boundary layer profile on the order of half the inlet height. The internal diffusion requirement of the inlet is reduced, resulting in a smaller inlet volume and weight. The data indicates that the streamwise diffusion scheduling is critical to inlet performance in regards to separation and distortion.

The power savings coefficient (PSC) depends only on the ingested profile. This performance metric relates to both reduced drag and wake recovery made possible by BLI and re-energizing the wake. As shown in Section 5.2.1, the propulsive power requirement for the simulated airframe section is reduced by as much as 23%. However, system level fuel savings depends largely on the performance of the embedded engine. Performance losses associated with reduced pressure recovery (measured as low as 90%, Figure 43) and large distortions (Figure 44) will erode the power savings [10]. The fuel savings will be less than 23% when engine response is accounted for. The literature indicates that the core performance loss is much more sensitive to distortion and total pressure losses than the fan, and a modified duct design that locates the distortion profile in the fan duct only will improve embedded engine performance and increase the fuel savings [22].

8.3 Flow within BLI S-ducts

The fundamental flow study experiments led to several key observations regarding BLI S-duct behavior. The low-momentum of the thick ingested boundary layer is prone to separation due to diffusion and duct curvature. These separations substantially increase AIP distortions and total pressure losses. Proper area and offset scheduling that accounts for local curvature, pressure gradients, and area diffusion could help to reduce separation and improve the AIP distortion levels.

The secondary flows associated with the inlet throat corners and duct offset play a governing role in the development of the flow within the S-duct. Although these vortices were not measured directly, their effects are observed at the AIP total pressure profile. The vortices concentrate the ingested boundary layer as well as the duct boundary layers at the bottom of the AIP. In effect, the secondary flows prevent mixing of the boundary layer with the main flow. The result is a pocket of large total pressure deficit at the AIP. In general, the AIP distortion is a result of ingested boundary layer health, secondary flows, free stream Mach number, and separations.

Static pressure gradients determine all aspects of flow development within serpentine inlets. The flow area affects the average “global” static pressure across the flow plane and the wall curvature affects the “local” static pressure gradient. The “global” and “local” pressure gradients combine to determine local flow behavior. Total pressure recovery in serpentine diffusers is a function of skin friction and separation. Separation greatly reduces the total pressure recovery and should be avoided. Distortions due to separation can cause more severe problems with inlet/engine compatibility than boundary layer ingestion. The negative effects of separation near the AIP can be worse than separation further upstream in that the inlet-induced separation does not relax before reaching the AIP.

8.4 Flow Control as an Enabling Technology

Numerous serpentine inlet studies indicate that flow control is necessary to enable short, high-offset BLI diffusers. An important issue with passive control (such as vortex generator vanes) and active controls that inject flow is that the distortion profile is not removed. Rather, the total pressure deficit is shifted from a circumferential to a radial distortion pattern. The bleed control utilized in this study removed the low-energy boundary layer, which reduced the circumferential distortion without increasing radial distortion intensities. This result marks a performance improvement over passive control schemes such as vortex generator vanes, which redistribute the low-energy boundary layer air. In effect, vortex generator vanes reduce the circumferential distortion by shifting the pattern to a radial distortion.

Here, the distortion was moved away from the center of the duct. By positioning the distorted low total pressure region of the AIP profile in the bypass duct, the core performance of an embedded engine will be improved. The fuel savings for a distortion of this type will be larger than that of a profile that allows distorted air to enter the core. The cost to system level performance of any active control is a power requirement. The power requirement to bleed 2% of the inlet mass flow is not trivial. However, unlike injection, the bleed air can be integrated into other aircraft systems, such as the ECS. By making use of the bleed air, system level benefits can offset the power cost associated with active control.

Chapter 9

Conclusions and Recommendations

9.1 Conclusions

1. The Virginia Tech BLI wind tunnel is a unique facility that allowed the testing of BLI serpentine inlets under realistic operating conditions. The test results produced increased knowledge of the nature of flow distortions produced by the ingestion of large boundary layers and duct geometry effects. The resulting measurements lead to important observations related to embedded engine systems and serpentine inlet design. First, the intensity of AIP distortions was demonstrated to be associated with the growth of the lower boundary layer and separations in the serpentine duct. Second, analysis showed that these flow behaviors resulted from the properties of the ingested boundary layer and the internal duct shaping. Third, duct offset, curvature, and area scheduling caused separations and pooling of the ingested boundary layer air at the AIP. Finally, these distortions reduced inlet pressure recovery.
2. Flow control experiments demonstrated the ability to reduce the distortion intensity by employing an active bleed system. This bleed system utilized two suction ports, one located at the forward end of the BLI inlet and one located at the aft near the AIP. The bleed flow was induced by vacuum systems connected to the lower duct bleed slots. At the maximum bleed flows of approximately 2% of the total serpentine inlet flow, distortion intensity was reduced by an average of 19-36%. Further improvement in distortion intensity should be possible with increased control flows. The performance of the bleed flow control method may offer a benefit over other control methods by more effectively managing the total pressure distortion, simplifying system-level integration.
3. The BLI inlet is shown to be only a part of the inlet/diffusion system. The full system also involves the flow pattern and diffusion that occurs over the airframe. Inspection of the flow profile at the throat of the inlet (Figure 18) indicated a total pressure loss over the simulated airframe, upstream of the S-duct. Total pressure losses also

occured within the S-duct as a result of separations and internal flow development (Figure 29). The total pressure ratio and efficiency of the diffusion system therefore depend on both the airframe and the serpentine inlet. Less diffusion is required in boundary layer ingesting inlets because a portion of the deceleration of the flow occurs over the airframe. The diffusion occurs regardless of whether the propulsion system is ingesting the airframe boundary layer, and the power savings is based on this fact. The deceleration is manifested by a reduced average velocity entering the S-duct.

4. Analysis shows that boundary layer ingestion can lead to significant power savings. For the wake simulated in this study, the ideal power required to maintain flight is reduced by up to 23%. Traditional engines that are not designed to operate under distorted conditions will suffer degraded engine performance, offsetting this power savings. An opportunity for integrated design of the inlet and engine system exists to obtain a vehicle-level fuel burn reduction. This integrated approach will involve design, modelling, and validation. Studies of engine response to distortion will provide a fundamental understanding of the physical processes governing engine behaviors, and guidelines for the design of distortion-tolerant engines.

9.2 Recommendations

1. Two areas of concern for inlet/engine matching in embedded systems are stability and performance. ARP1420 methods provide a framework for analyzing the effects of distortion on stability. Knowledge of the complete velocity and pressure field is required to fully investigate effects on engine performance. Therefore, experiments measuring the velocity magnitude and direction across the AIP are necessary to estimate embedded engine response. Direct measurement of engine response to total pressure distortions, such as monitoring fan blade wakes when subjected to distortion, will provide useful data related to the performance loss mechanisms associated with BLI/S-duct engine systems.
2. Flow control was shown to be effective in improving AIP distortion and therefore engine operability. However, careful duct design to reduce distortion without the added cost and reliability concerns of active control may be possible. A study that includes analysis of multiple duct geometries and inlet boundary layers (resulting from airframe design changes) could alleviate the negative impacts of distortion on embedded engines without the need for active flow control.
3. By determining the mechanisms of engine response to distortions and reducing distortions through duct/airframe design changes, methods for designing distortion-tolerant fans can be reached. These distortion-tolerant fans would enable operation of embedded engines, without operability concerns or flow control requirements. The efficiency

of these fans will likely be reduced when compared to modern high-performance fans that are designed with little margin. However, system-level benefits of BLI may yield reduced airplane fuel burn.

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Appendix A

Measurement System and Uncertainty Analysis

A.1 Measurement System

The pressures reported in this study were recorded using a digital data acquisition system. Eighty Omega PX139 Series pressure transducers with a 5 psi range were employed. A National Instruments PXI-6255 multifunction DAQ card measured the voltage output of the transducers and a computer recorded the results. Table 6 provides the performance specifications of the transducers as provided by the manufacturer and computed pressure uncertainties. The National Instruments PXI-6255 multifunction DAQ card has a rated resolution uncertainty of $\pm 0.5 \cdot 10^{-6}$ Volts.

Table 6: Pressure Measurement System

PX139-005D4V	Uncertainty (%)	Uncertainty (PSI)
Linearity and Hysteresis	$\pm 0.1\%$ FS	± 0.005 PSI
Repeatability	$\pm 0.3\%$ FS	± 0.015 PSI
Zero Temp Effects	$\pm 0.5\%$ FS	± 0.025 PSI
Span Temp Effects	$\pm 0.5\%$ FS	± 0.025 PSI

A.2 Uncertainty Analysis

This section provides an uncertainty analysis of the pressures recorded using the data collection system described above. Following the methods of Figliola and Beasley [13], the

pressure measurement uncertainty is estimated using the rated performance of each component. The first consideration is the zero-order instrument uncertainty, u_0 . The zero-order uncertainty provides an estimate of the expected random uncertainty caused by data scatter due to reading the instrument. Equation A.1 computes the uncertainty in the PXI-6255 voltage measurements.

$$\begin{aligned} u_0 &= \pm \frac{1}{2} resolution \\ &= \pm 0.5 \cdot 10^{-6} v \end{aligned} \quad (A.1)$$

The pressure transducers produce a voltage output proportional to the applied pressure over a 4 volt range. Equation A.2 computes the resulting pressure uncertainty.

$$\begin{aligned} u_{0_{PXI}} &= \frac{5psi}{4v} \cdot 0.5 \cdot 10^{-6} v \\ &= 6.25 \cdot 10^{-7} psi \end{aligned} \quad (A.2)$$

As Equation A.2 shows, the uncertainty in the pressure measurement due to the DAQ card is very small. Following a similar method, the resolution uncertainty of the mercury manometer that calibrated the transducers is computed (Equation A.3).

$$u_{0_{manometer}} = \pm 0.05 inHg = \pm 0.02455 psi \quad (A.3)$$

The instrument uncertainty for the PX139 pressure transducers is computed by combining the elemental errors (Table 6) using the RMS method [13], as shown in Equation A.4.

$$\begin{aligned} u_{x_{PX139}} &= \pm \sqrt{\sum_{k=1}^{k=n} e_k^2} \\ &= \pm \sqrt{\left(\frac{0.1 \cdot 5psi}{100}\right)^2 + \left(\frac{0.3 \cdot 5psi}{100}\right)^2 + \left(\frac{0.5 \cdot 5psi}{100}\right)^2 + \left(\frac{0.5 \cdot 5psi}{100}\right)^2} \\ &= \pm 0.0387 psi \end{aligned} \quad (A.4)$$

Finally, the overall maximum uncertainty is estimated by combining the component uncertainties using the RMS method, as shown in Equation A.5.

$$\begin{aligned} u_d &= \pm \sqrt{u_{0_{PXI}}^2 + u_{0_{manometer}}^2 + u_{x_{PX139}}^2} \\ &= \pm \sqrt{(6.25 \cdot 10^{-7} psi)^2 + (0.02455 psi)^2 + (0.0387 psi)^2} \\ &= \pm 0.046 psi \end{aligned} \quad (A.5)$$

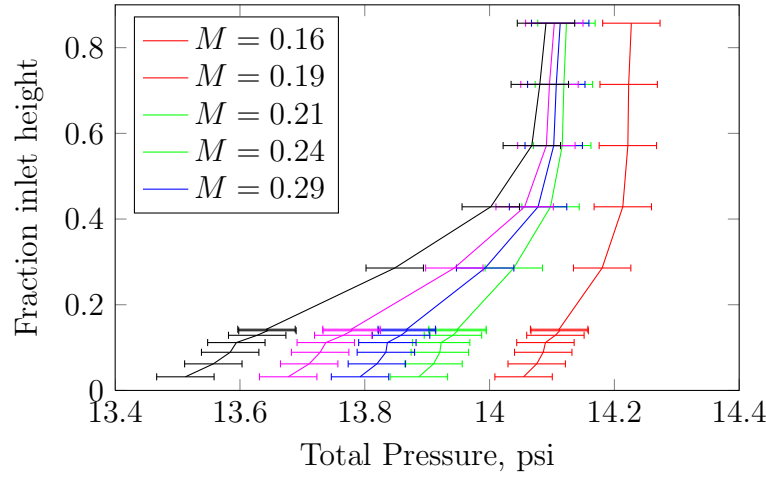


Figure 49: Centerline S-duct Throat Total Pressure Profiles

This uncertainty in the pressure measurements of $\pm 0.046 \text{ psi}$ represents the worst-case value. The computation of this uncertainty assumes that all errors occur in the worst possible way for all components of the measurement system. The following sections provide several key figures from the Results sections, with error bars added.

Inlet Conditions

Figure 49 repeats the centerline boundary layer profiles that were ingested by the S-duct. For each total pressure profile, error bars are added that show the maximum error confidence interval. The confidence interval occupies a larger fraction of the measurement range for the low speed cases as compared to the higher speed cases. However, the profiles follow the expected trend of increasing total pressure deficit as the flow speed increases. Combining this observation with the overall ingested profiles measured at 78 locations (Figure 18), any measurement errors tend to disappear in the average as expected.

Wall Static Measurements

The static pressure distributions along the top and bottom walls of the S-duct showed a large variation in pressure. Figure 50 provides plots of the top and bottom wall static pressures, with the error bars added. The worst-case error intervals are small relative to the overall range of pressures along each wall. The result is that the trends in the measured pressures do not change within the maximum error interval, and the observations drawn from them remain unaltered.

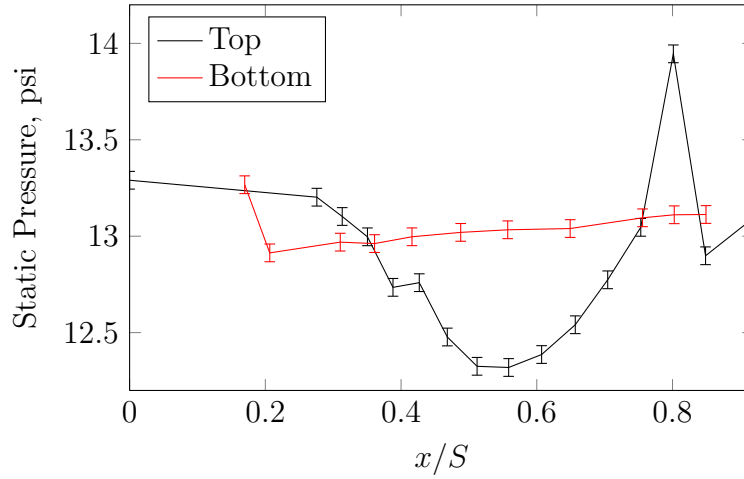


Figure 50: Centerline Top and Bottom Wall Static Pressures, $M = 0.29$ case

AIP Total Pressure Distribution

Repeating the unwrapped AIP plots from Figure 31, Figure 51 shows the recorded pressures along with the confidence intervals. Once again, the error intervals are small relative to the overall variation in total pressure, and trends remain unaltered. The values computed following ARP1420 methods to quantify circumferential distortion intensity directly depend on the measured AIP total pressures. The value of circumferential distortion intensity is sensitive to changes in total pressure. However, the trends in distortion intensity remain unchanged for total pressure values within the confidence interval.

A.3 Uncertainty Analysis Summary

The instrumentation employed in this study was chosen based on the manufacturers' performance specifications. These devices were documented by the manufacturers and shown to be adequately accurate. The computed confidence intervals were small relative to the pressure variations that were measured in the experiment. Thus, the trends presented in the Results sections are unaltered by any errors occurring within the specified limits of the instruments. Based on the fact that the observed trends followed theoretical expectations, there is also a high degree in confidence that no system-level errors occurred while measuring the pressures that are reported in this thesis.

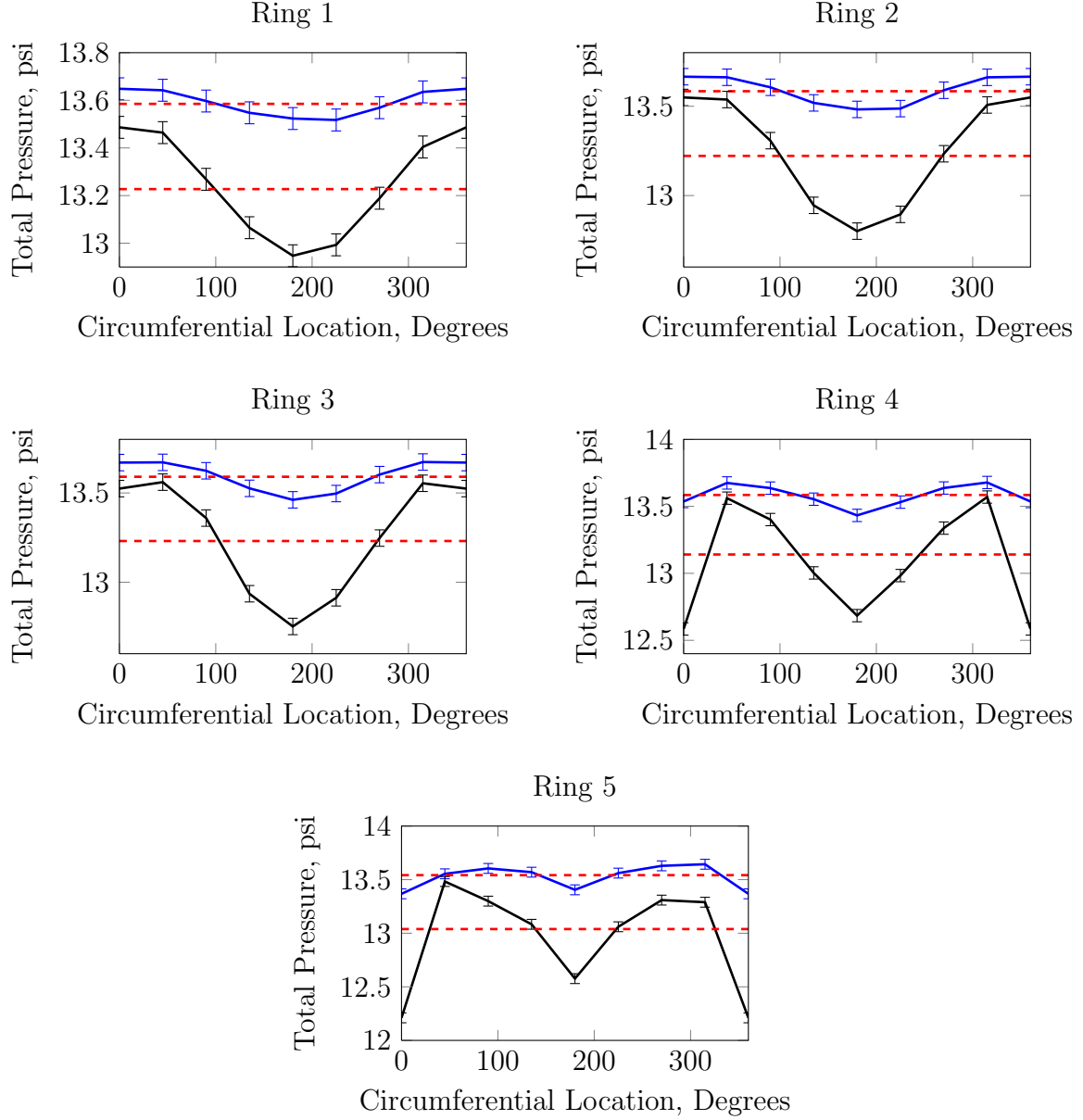


Figure 51: AIP Total Pressures By Ring for $M = 0.16$ (blue) and $M = 0.29$ (black) cases

Appendix B

Estimation of the Static Pressure Distribution Across the S-duct Inlet Plane

As noted above, the total pressure can be extrapolated from the total pressure rake positioned in the throat of the S-duct. In this way, using the fact that $P_0/P = 1$ for a velocity of zero (no slip condition), the static pressure across the boundary layer region of the flow can be estimated. This spline extrapolation is shown in Figure 52.

The value extrapolated at $y = 0$ is the approximate value of the static pressure. This value for static pressure holds across the entire height of the boundary layer region, according to the boundary layer assumptions. Fixing the value of static pressure across the boundary layer region, and using the measured static pressure at the top of the throat, a linear interpolation was applied to compute the variation of static pressure across the entire height of the inlet. The interpolated static pressures are shown in Figure 53 normalized against atmospheric pressure.

These interpolated static pressures were used in the computation of the local velocities provided in Figure 23.

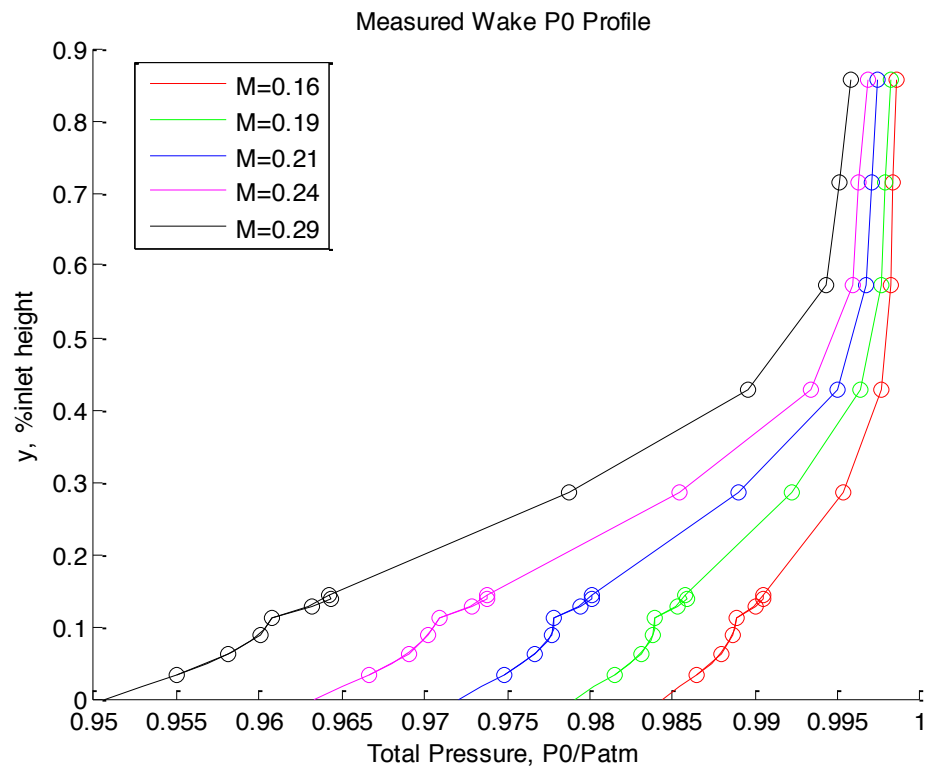


Figure 52: Centerline S-duct Throat Total Pressure Profile, extrapolated to wall for boundary layer static pressure estimate

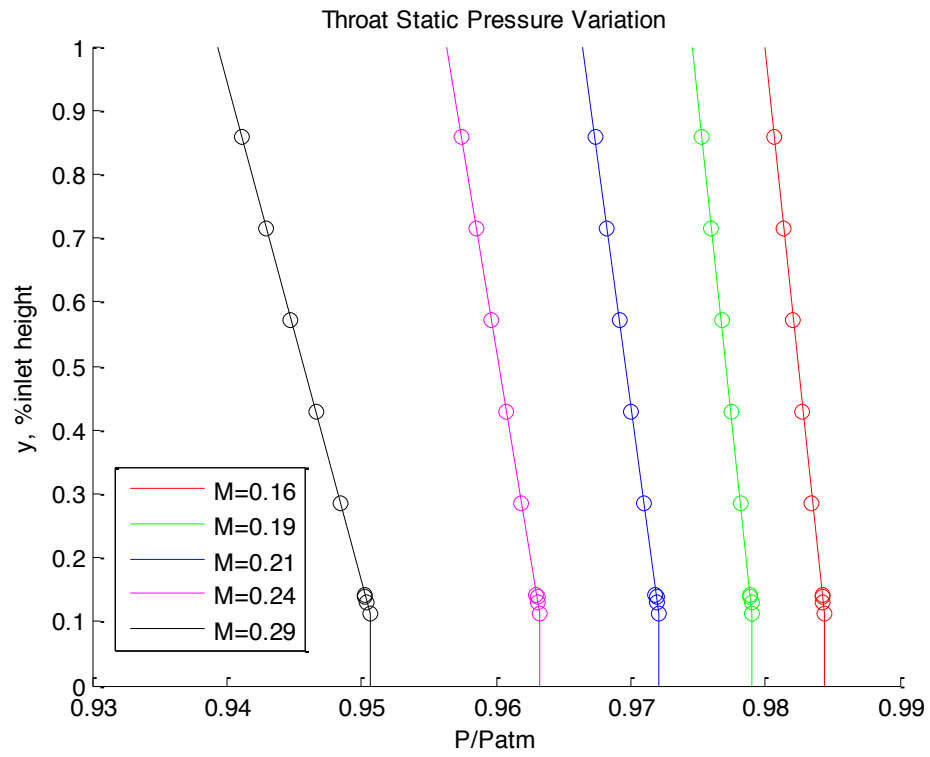


Figure 53: Interpolated static pressure distribution across throat of S-duct, for each speed tested

Appendix C

Errors in computed velocity due to static pressure variations

As Equations 3.1 and 5.3 show, the value of velocity depends strongly on the ratio of P_0/P . Holding the total pressure constant for the sake of the analysis, and taking the largest variation in static pressure from Appendix B (1.2%), the change in velocity associated with the change in static pressure can be computed. Figure 54 shows a plot of velocity versus P_0/P .

As can be seen, the value of static pressure becomes most important at very low and very high speeds. A small change in P_0/P leads to a large change in velocity. Taking the static pressure variation measured across the throat of the duct and a characteristic value of 71 m/s for velocity, the plot of Figure 54 shows a large change in velocity (23%). In the flow speeds of this test, a small change in static pressure (1.2%) can lead to a large change in velocity (23%). This variation is the reason that an accurate knowledge of the static pressure is required to compute velocities properly.

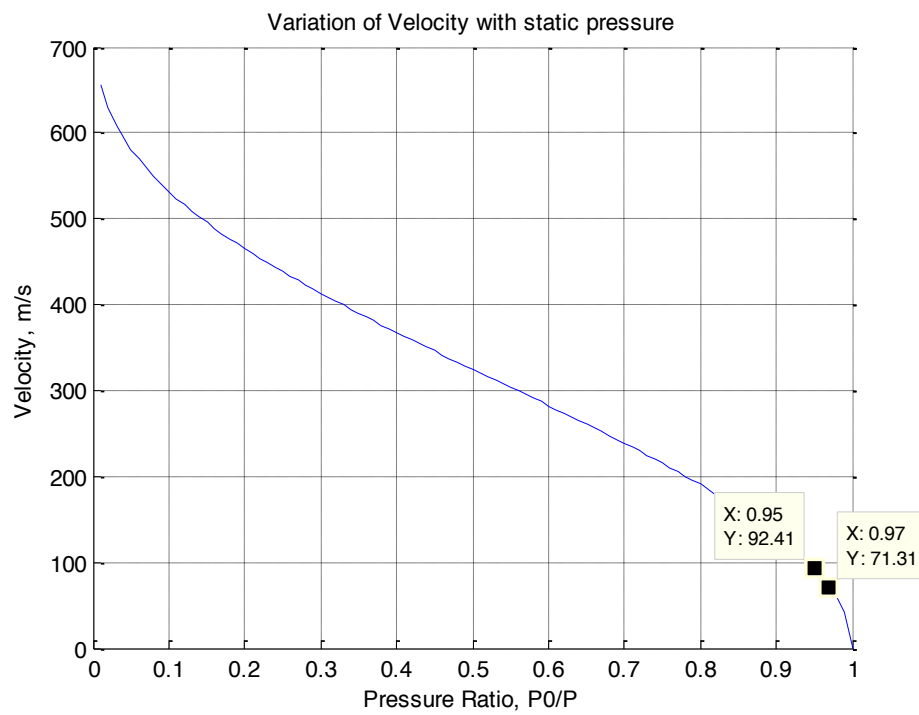


Figure 54: Variation of velocity with static pressure. p_0 held constant while value of p was varied

Appendix D

Definition and calculation of wake shape parameters

The following equations were used in the calculation of the wake shape parameters and power saving coefficient. The method followed was presented by Smith [32]. Values pertinent to the results are presented Table 4. δ represents the non-uniform wake thickness. V_W represents the wake velocity and varies across the wake thickness. V_0 is the wake free-stream velocity, and ρ represents the fluid density. Because the wake was shown to be uniform in the transverse direction (Figure 19, dA uses a unit depth in the transverse direction. The form factor is of particular importance as a means of validating tunnel performance and estimating the power savings associated with BLI. The wake form factor of approximately 2 is reasonable for the trailing edge of an airfoil in which a large amount of diffusion occurs before reaching the S-duct, positioned near the trailing edge.

Wake Displacement Area

$$\delta^* = \int_0^\delta \left(1 - \frac{V_W}{V_0}\right) dA \quad (D.1)$$

Wake Momentum Area

$$\Theta = \int_0^\delta \frac{V_W}{V_0} \left(1 - \frac{V_W}{V_0}\right) dA \quad (D.2)$$

Wake Pseudoenergy Area

$$k = \int_0^\delta \frac{V_W^2}{V_0^2} \left(1 - \frac{V_W}{V_0}\right) dA \quad (D.3)$$

Drag of Body

$$D = \rho V_0^2 \Theta \quad (D.4)$$

Wake Form Factor

$$H = \frac{\delta^*}{\Theta} \quad (D.5)$$

Pseudoenergy Coefficient

$$K = \frac{k}{\Theta} \quad (D.6)$$

Power Saving Coefficient

$$PSC = \frac{\sqrt{1 + C_{TH}} - K}{\sqrt{1 + C_{TH}} + 1} \quad (D.7)$$

Thrust-Loading Coefficient

$$C_{TH} = \frac{\frac{\delta^*}{\delta} \left(2 - \frac{\delta^*}{\delta} \right)}{H \left(1 - \frac{\delta^*}{\delta} \right)} \quad (D.8)$$