Low-Speed Performance Enhancement using Localized Active Flow Control

Integration Study of Localized Active Flow Control on a Performance Reference Aircraft (3/4)

Paul Vijgen, The Boeing Company
Alex Ziebart, The Boeing Company
Arvin Shmilovich, The Boeing Company
Rene Woszidlo, The Boeing Company

April 27, 2022

Table of Contents

List of Figures

List of Tables

Nomenclature

Parameters

A_{ref}	Wing reference area
α	Angle of attack
β	Yaw angle
C_D	Airplane drag coefficient
C_L	Airplane lift coefficient
$C_{L,max}$	Maximum lift coefficient
C_m	Airplane pitching moment coefficient
C_μ	Total momentum coefficient, $\dot{m}u_j/(0.5\cdot\rho_\infty u_\infty^2 A_{ref})$
C_p	Pressure coefficient
C_q	mass flow coefficient, $m_j/(\rho_\infty u_\infty A_{ref})$
L/D	Lift-to-drag ratio
M	Mach number
$\dot{m}$	mass flow, lbs/sec
P_{0in}	Total pressure at the actuator inlet
$P_{0\infty}$	Freestream total pressure
PR	Total pressure ratio, $P_{0in}/P_{0\infty}$
Re	Reynolds number based on mean aerodynamic chord
T_{0in}	Total temperature at the actuator inlet
$T_{0\infty}$	Freestream total temperature
TR	Total temperature ratio, $T_{0in}/T_{0\infty}$
$\mathbf{U}$	Velocity vector
u_∞	Freestream velocity
V	Aircraft speed
x,y,z	streamwise, spanwise and vertical coordinates, resp.

Subscripts

App	approach
in	actuator inlet
j	actuation jet
th	actuator throat
∞	freestream
0	stagnation

Abbreviations

A/C	Air Conditioning
AFC	Active flow control
APU	Auxiliary Power Unit
CAC	Cabin Air Compressor
CRA	CFD Reference Aircraft
CFD	Computational Fluid Dynamics
EAI	Engine Anti Ice
ECS	Environmental Control Systems
FHA	Functional-Hazard Assessment
IB, OB	Inboard, outboard
LDG	Landing
LE	Leading edge
MMEL	Master Minimum Equipment List

NASA	National Aeronautics and Space Administration
NGS	Nitrogen Generation System
OEW	Operating Empty Weight
PRA	Performance Reference Aircraft
TAT	Total Air Temperature
TKO	Takeoff
WAI	Wing Anti Ice

Executive Summary

A study of conceptual integration and performance aspects of localized active flow control (AFC) technology onto wings of short-to-medium-range project passenger airplanes is summarized. Using predicted aerodynamic performance improvement opportunities on the CFD Reference Aircraft, estimated benefit opportunities for conceptual implementation of studied wing localized active flow control (AFC) technology for low-speed (takeoff and landing) application on a Performance Reference Aircraft configuration are presented. Using conceptual AFC systems and structural integration weight penalties for studied concepts, potential relevant net performance benefits can be obtained with reliable AFC in takeoff and landing. The conceptual integration study identifies potential promising localized wing AFC application opportunities for high-lift conditions using energy sources for modern aircraft. Material benefits are estimated for takeoff and landing configurations for selected localized AFC applications. Next steps to refine and expand results of investigated topics, as well as possible other local AFC wing applications, are suggested.

1 Introduction

The opportunity for improved aerodynamic efficiency at low-speed flight conditions on modern passenger aircraft through the application of AFC has motivated several aerodynamic as well as integration studies and tunnel and flight tests in two decades [1-7]. AFC at subsonic low-speed conditions in the takeoff and landing phase can conceptually provide significant flow-separation control on simple-hinged wing flaps, and, hence could allow potential reduced flap areas – however at the penalty of significant mass flow requirements that would dictate significant architectural changes to the aircraft [2]. As a result, application of such simple-hinged flap AFC rendering is likely not practical in the foreseeable future for modern passenger aircraft configurations with highly integrated and efficient state-of-the-art wing high-lift systems.

A pathway toward more practical implementations might utilize more localized wing AFC applications with limited architectural impact on the aircraft. Instead of complete redesign of high-lift structural layout and aircraft systems to reliably supply significant AFC mass flow at high pressures, the prospective use of localized AFC applied to smaller regions on existing wing high-lift trailing and leading edge elements may offer meaningful net performance enhancements with manageable system integration. In particular in view of potential opportunities to use already available energy sources on-board of modern aircraft. As is shown in final report document #2 [8], CFD simulations point to relatively modest AFC energy (mass flow and pressure ratios) to provide possible relevant aerodynamic benefits.

Localized AFC applications to commercial transports may lead to environmental and economic advantages for airplane operators. In particular, high-lift performance is one of the key objectives and integration constraints in integrated aircraft design. Considering takeoff as an example, since the lift-to-drag ratio (L/D) is a major determinant of performance (in particular on twin-engine aircraft), an increase in L/D could allow for potentially larger airplane payload, reduced runway length, or longer range, which translates to substantial economic advantages. The takeoff and climb-out portions of the flight profile can affect engine thrust requirements. Therefore, applications that improve the L/D in key takeoff scenarios may enable a reduction in the engine size, resulting in lower airplane weight, lower fuel consumption and reduced emissions (including community noise). Also for takeoff, a potential increase in C_L at given angle of attack, as well as increase in $C_{L,max}$ in takeoff can affect takeoff speed, speed schedules and takeoff field length performance. Increase of lift at a given angle of attack may alleviate attitude constraints at rotation during takeoff – potentially facilitating integration of airplane-family members with different fuselage lengths. Landing performance is largely driven by $C_{L,max}$ of a wing with flaps in landing detent, and increased $C_{L,max}$ allows reduced V_{app} for given wing size. AFC applications studied in Section 2 suggest an opportunity for relevant changes in $C_{L,max}$ in the landing configuration.

Promising approaches identified in this study target different areas of the wing for localized AFC implementation. In one application, AFC is used to improve aerodynamic performance of ailerons, which are customarily deflected ("symmetric aileron droop") during selected high-lift operations. AFC can also be used at specific locations on the wing leading edge region in conjunction with slats or nacelle/pylon in order to enhance performance of the high-lift system. Both aileron hingeline AFC and selected wing LE applications have been explored in CFD on the Reference Aircraft (final report document #2 [8]). Available CFD results suggest potentially relevant improvement opportunities in key aerodynamic parameters that can affect low-speed high-lift performance and integration.

The overarching objective of current study is to scope potential performance and integration opportunities for some localized AFC wing applications. Within the scope and the resources of current Study Contract, conceptual AFC systems integration and resulting performance assessment for aileron and wing LE AFC applications is studied at a conceptual level. One goal is to assess which studied localized applications would benefit from further more detailed studies (e.g., as part of technology development portfolios for future commercial aircraft aimed at increasing TRL level needed for product-development assessment).

In this Report, results of conceptual integration studies using several AFC layouts and energy sources are considered for the aileron and wing LE applications. Systems assessment is done both for already available energy sources on modern aircraft, as well as for possible additional systems, resulting in estimated AFC related systems penalties. Next, integration layouts of AFC pressure lines and (conceptual) integration in typical existing systems layouts are used to determine AFC systems weight and assess feasibility of integration. The predicted aerodynamic AFC increments on the CFD Reference Aircraft are translated to the Performance Reference Airplane (PRA) configuration, including trim, aeroelastic, and structural loading effects.

For a localized AFC applications studied, next conceptual airplane-level performance increments are estimated using the aerodynamic and weight increments for the PRA. Conceptual operational systems requirement considerations to support the low-speed AFC applications are summarized for studied energy sources. Based on available study results, recommendations concerning possible follow-on integration studies on localized wing AFC are provided.

2 Integration Study Setup

This Section provides information on the project aircraft configuration used as the Performance Reference Aircraft (PRA) in current conceptual AFC integration assessments. First, the analysis approach used to scope potential AFC increments is outlined, followed by description of the Performance Reference Aircraft. This is followed by a summary of key aerodynamic increments enabled by selected wing AFC topics as translated onto the Performance Reference Aircraft, including a summary of effects included in translation of AFC increments on the computational Reference Aircraft (CRA). The aerodynamic increments summarized here are combined with AFC energy-source increments (Section 3) into performance benefits analysis in Section 4.

2.1 Study Analysis Approach

The CFD results for various AFC applications and settings on the CRA configuration in the CFD Report have been used to develop increments in key aerodynamic performance parameters for the PRA configuration. This Section provides a summary of key aerodynamic AFC increments that are relevant for low-speed takeoff and landing performance assessment of the AFC wing applications studied here. The aerodynamic AFC increments are combined in Section 4 with AFC weight increments (Section 3) towards performance impact assessment of AFC opportunities. Figure 1 provides a schematic outline of inputs and increments used to assess Performance opportunities on the PRA in current study.

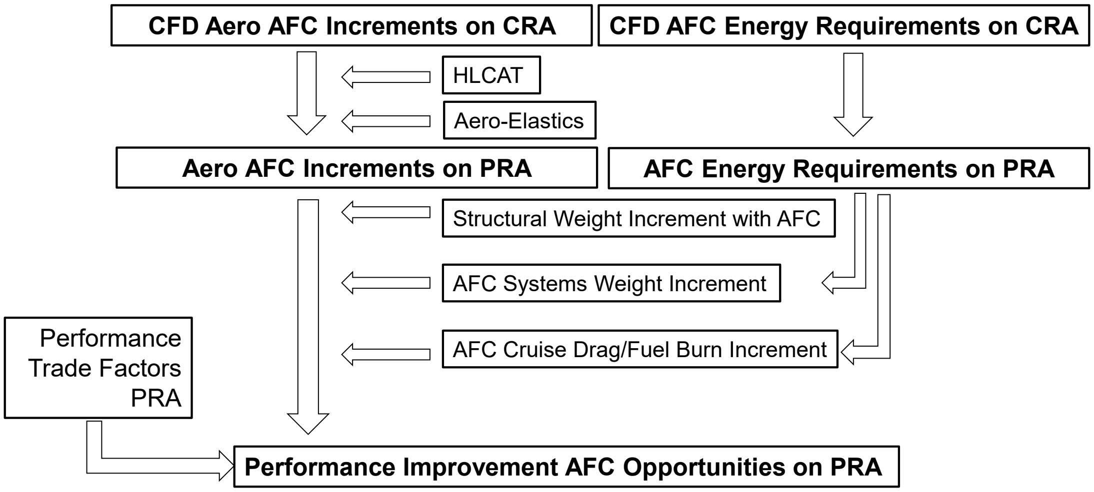

Figure 1 – Analysis steps of conceptual AFC study (CRA=CFD Reference Aircraft; PRA=Performance Reference Aircraft).

AFC increments and energy requirements defined using the CRA configuration are translated to the PRA configuration, and are combined with AFC related structural, systems and possible cruise penalties (e.g., additional excrescence drag of exposed AFC actuators in the cruise configuration – with flaps retracted).

2.2 Performance Reference Aircraft Configuration

This section provides introduction to the Performance Reference Aircraft (PRA) used in current conceptual integration and performance increment study. Figure 2 shows the conceptual PRA planform and key high-lift movable geometry elements. The planform is representative for product-development project studies for possible future short-to-medium range single-aisle passenger aircraft. Inboard and outboard flap have Fowler motion, and the aileron is symmetrically drooped in takeoff (assumed 7.5° in current study). The illustration in Figure 3 does not show wing spoilers or nacelle/nacelle-pylon located between LE devices 4 and 5. Consistent with the computational CRA configuration used (Figure 3), LE device 5 is a

Krueger flap, whereas LE devices 1 – 4 are 3-position slats (i.e., retracted in cruise, sealed for takeoff, and gapped for landing flap settings).

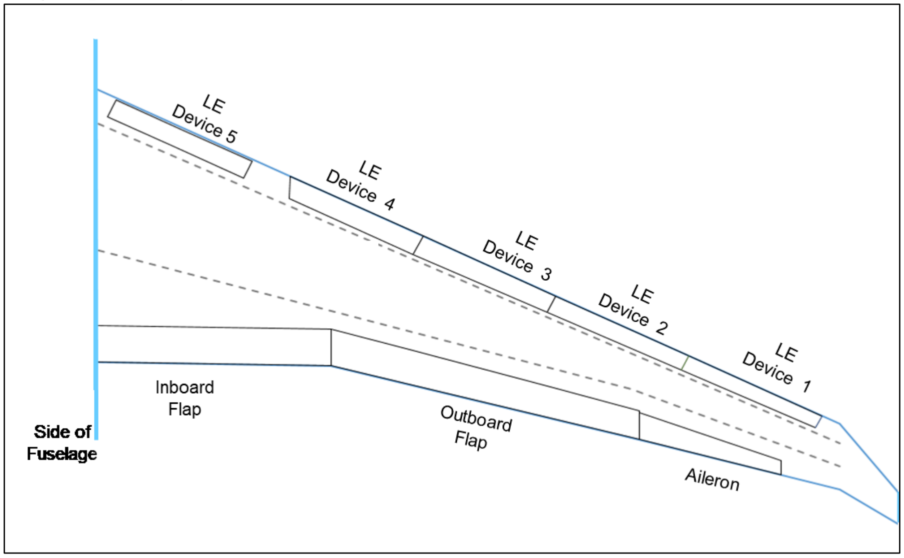

Figure 2 – Schematic wing planform and high-lift elements on Performance Reference Configuration.

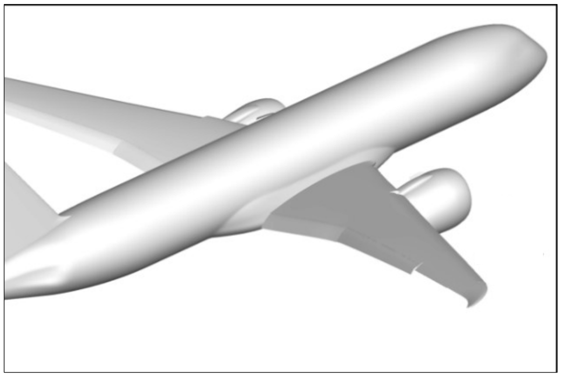

Figure 3 – Performance Reference Aircraft has similar wing planform shape as CRA (shown).

The wing planform shape of the Performance Reference Aircraft is aerodynamically very similar to the Computational Reference Aircraft Configuration (CRA) used in the numerical study in the final report document #2 [8]. In particular, the wing design Mach number, aspect ratio, wing sweep, taper ratio and span of high-lift devices (relative to wing span) and aileron chord ratio are similar to the CRA. The high-lift technology (leading edge architecture and trailing-edge Fowler flap design without spoiler droop in the CRA geometry) used in this study for the CRA configuration is identical (other than scale). Since the Performance Reference Aircraft is a somewhat smaller aircraft than the CRA, flap-chord ratio and flap area ratios are somewhat different on the PRA configuration. For the purpose of current scoping study, the low-speed wing aerodynamic trends and AFC increments predicted by CFD for the CRA are applicable to the PRA configuration.

2.3 Key Aerodynamic AFC Increments on Performance Reference Aircraft

This section provides a summary of key aerodynamic increments due to AFC on the Performance Reference Aircraft for studied AFC concepts topics, after adjustments for the PRA configuration relative to the CRA project configuration, as well as after adjustment for effects not included in the CFD modeling on the CRA.

2.3.1 Aileron AFC Aerodynamic Increments

Takeoff and landing aerodynamic increments are summarized for studied aileron AFC applications.

2.3.1.1 Aileron AFC Aerodynamic Increments – Takeoff

The CFD results for the aileron AFC application and settings on the CRA configuration have been scaled and trimmed to account for the geometry differences between PRA and CRA using the Boeing proprietary HLCAT (High Lift Configuration Analysis Tool) performance polar buildup method. The CRA configuration did not have a horizontal tail included in the CFD simulations. In addition, the HLCAT method incorporates thrust effects. The takeoff results presented in this section pertain to the takeoff flap detent (with leading edge slat elements in takeoff sealed position and the Fowler flaps deployed at typical moderate takeoff deflection.

As an example, Figure 4 summarizes the HLCAT derived changes in L/D in the takeoff configuration on the PRA for various aileron droops at a PR = 2.

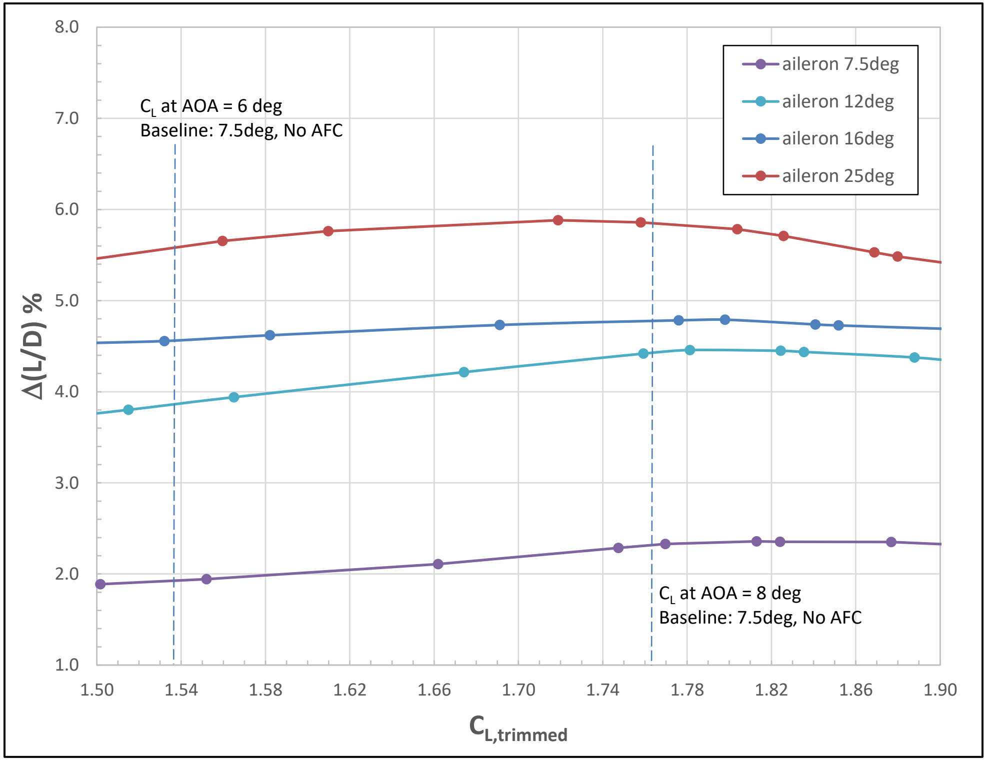

Figure 4 – Aileron AFC: HLCAT takeoff L/D increments for PRA (PR=2). Deltas relative to baseline aileron deflection (7.5°).

The CFD results for the CRA for various aileron deflections and AFC power settings were obtained for a rigid geometry (i.e., using the same nominal low-speed wing-twist and flap shapes/settings appropriate for takeoff or landing). Aeroelastic effects of changes in wing twist and camber due to modified wing spanwise loading with deeper aileron deflections / AFC application have been estimated using approximate aeroelastics corrections included in the resulting net aerodynamic AFC increments. The resulting adjusted 'net' AFC aileron L/D increments used for subsequent performance-impact analysis on the PRA configuration are summarized in Figure 4. Compared to CFD increments for AFC on the CRA aileron (final report document #2 [8]), the combined effect of polar buildup from CRA to PRA, trim and thrust effects, and aeroelastic corrections results in a reduction of up to ~2% in the AFC L/D increment. The estimated total ΔL/D opportunity of 3 – 5% for symmetric aileron deflection of 12 – 16° represents a significant aerodynamic potential in takeoff for the PRs considered.

Reflecting the CFD increments on the CRA used as a starting point, there is no additional aerodynamic benefit to consider deeper AFC aileron deflections beyond about 16°. Limiting aileron AFC droop application to smaller values than 20° will minimize potential adverse impacts on S&C (roll authority), aileron actuator sizing/integration and aileron structural weight.

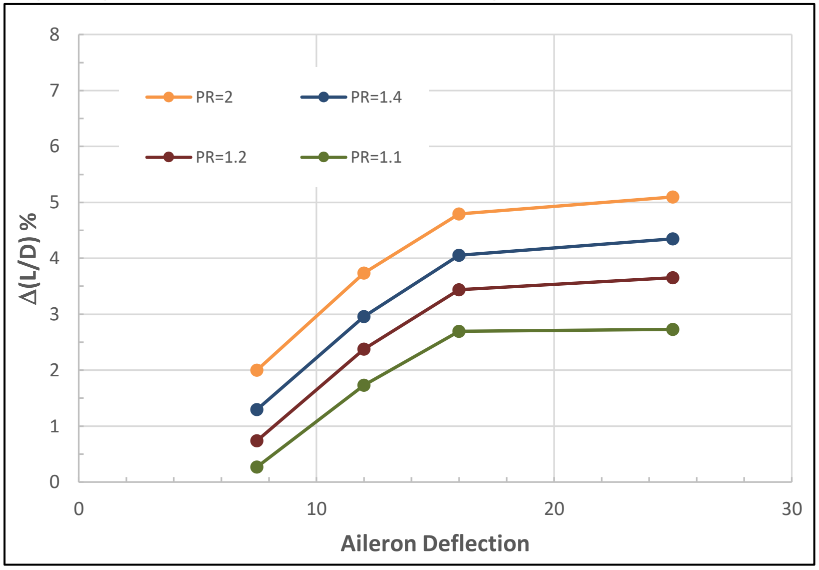

Figure 5 – Aileron AFC: Takeoff L/D increments for PRA including aeroelastic effects. Deltas relative to baseline aileron deflection (7.5°).

The AFC mass flow requirements on the CRA configuration via CFD (final report document #2 [8]) at analyzed freestream conditions have been adjusted to apply to operating conditions and geometry (size/area of the AFC actuators) of the PRA configuration.

Incorporation of AFC actuators on the wing can result in a (small) increase in wing excrescence drag at cruise if the actuators are exposed in cruise. As is further discussed in the Systems section below, the aileron AFC actuator at the aileron hingeline is assumed to result in a small aft-step (on the order of 0.10 in.) in the cruise wing shape. The resulting local change in turbulent boundary-layer development will result in a (small) fuel-burn penalty in cruise due to additional excrescence drag. This increment is included in the AFC performance assessments in Section 4.

Related, if AFC energy is supplied by APU during high-lift conditions operations (see later Sections in this report), operation of the APU requires the APU inlet door to be open during takeoff and/or landing – with concomitant airframe drag increase. This drag increase during the takeoff / landing phase is included as a reduction in AFC Delta L/D used for input to the performance assessment in Section 4.

Figure 6 summarizes estimated aileron AFC impact on trimmed $C_{L,max}$ for the PRA configuration at a typical takeoff Mach number. $C_{L,max}$ improvements with AFC of ~1–2% are predicted for aileron deflections of 12° – 16° due to increased camber that raises net lift.

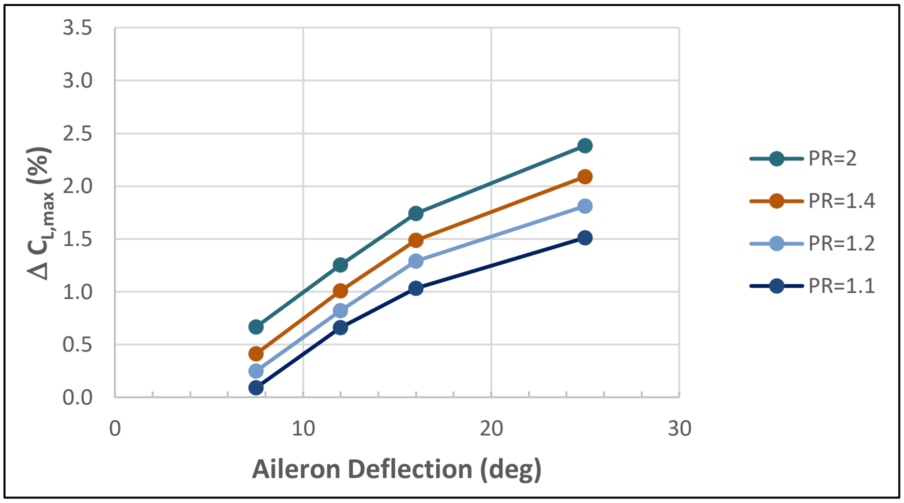

Figure 6 – Aileron AFC: Takeoff $C_{L,max}$ Increments for PRA including Aeroelastic Effects. Deltas relative to Baseline Aileron Deflection (7.5°).

2.3.1.2 Aileron AFC Aerodynamic Increments – Landing

The landing results presented next for the PRA configuration pertain to a landing flap detent (with leading edge slat elements positioned in landing gapped position and the Fowler flaps deployed at landing deflection. The PRA configuration used in current study has no aileron droop in the baseline configuration. The CFD simulations on the CRA also do not have aileron droop in the landing detent.

Following the approach and methods used to estimate the takeoff AFC increments, CFD increments on the CRA with AFC in the landing configuration were obtained for the PRA configuration, and aeroelastics effects were applied. Figure 7 summarizes the estimated improvement in lift at typical approach angles of attack for the CRA in the landing configuration. For aileron deflections of 12° - 16°, a significant increase of 2 – 3% in $C_{L,app}$ is predicted with AFC. This increased camber effect of the aileron deflection could translate in a relevant reduction in V_{app} of ~1–1.5%.

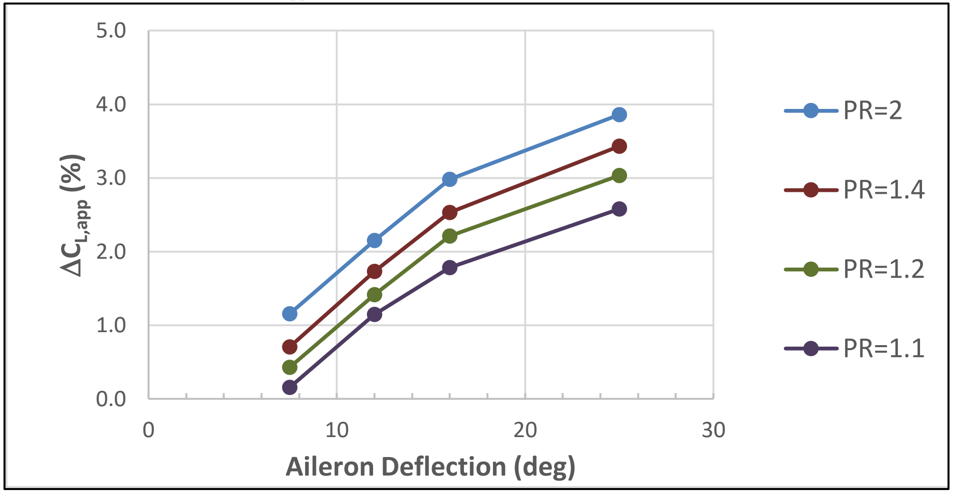

Figure 7 – Aileron AFC: Landing $C_{L,app}$ increments for PRA, including aeroelastic effects. Deltas relative to baseline aileron deflection (0°).

2.3.2 Leading Edge Wing at Outboard Slat AFC Aerodynamic Increments – Takeoff

Using CFD predicted AFC increments for the CRA, the build-up process was used to trim and scale landing increments to the PRA configuration for AFC applied to the leading edge wing at the most outboard slat (i.e., LE Device #1 in Figure 2). Aeroelastic effects (smaller than for the aileron AFC application) were included. Figure 8 shows resulting ΔL/D% increments for various PR settings from spanwise AFC actuation near the trailing edge of the slat (i.e., AFC actuator embedded in the fixed wing leading edge covered in cruise when slat is retracted.) The net ΔL/D increment for this AFC is 0.5 to 1.5% for actuation PR ranging from 1.6 to 4. At PR = 2, increment is ~0.75%. This AFC application in the wing leading edge provides a small increase in C_L at given angle of attack and no predicted change in $C_{L,max}$ (not shown here).

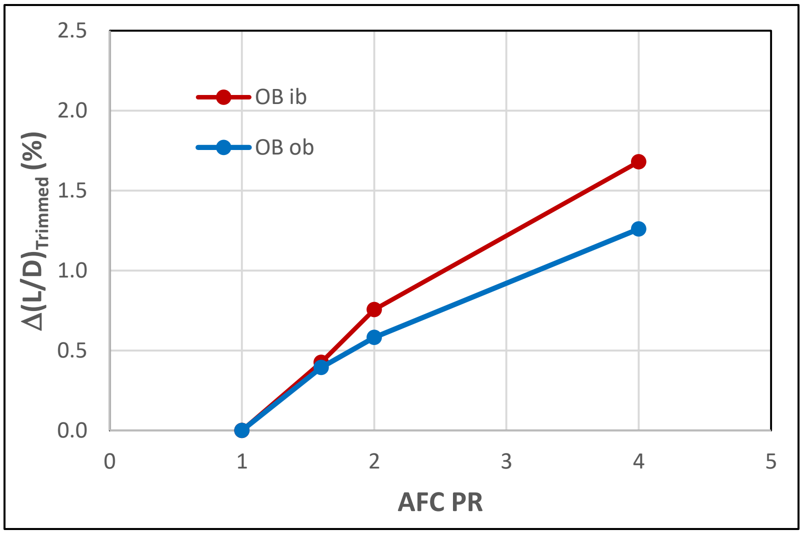

Figure 8 – AFC at Wing Leading Edge near Outboard Slat: Takeoff L/D Increments for PRA including aeroelastic effects. Deltas relative to Baseline Aileron Deflection (7.5°).

As is mentioned in final report document #2 [8], it is possible that tailored AFC actuation at this location may provide flow control opportunities at conditions not scoped in current study (e.g., flow control at certain angles in the juncture region at the most outboard slot).

2.3.3 Nacelle/Pylon/Wing Junction AFC Application Aerodynamic Increments

Using available CFD predicted AFC increments for the CRA for the takeoff configuration, the build-up process was used to trim and scale takeoff increments to the PRA configuration for a representative AFC actuation layout applied to the leading edge wing in the nacelle/pylon/wing junction (final report document #2 [8]). The L/D increment due to AFC for the Takeoff setting is ~0.3% at PR=1.6 to 0.5 – 1% at PRs of 2 and 3.

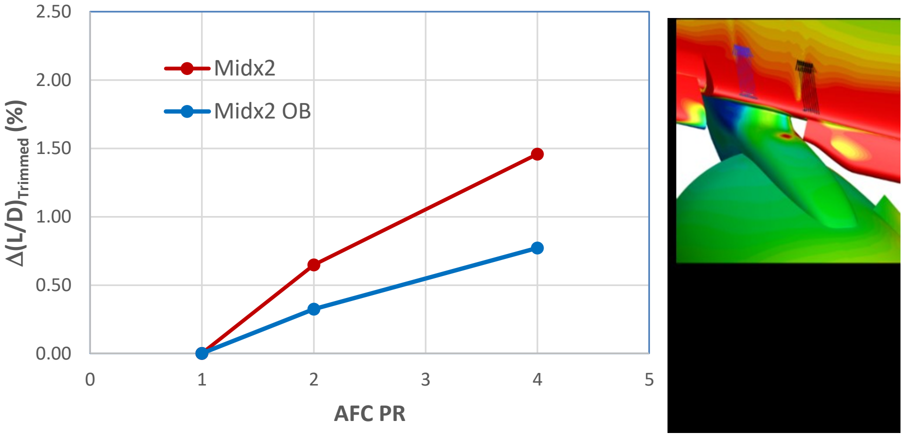

Figure 9 – AFC at Nacelle/Pylon/Wing Junction: Takeoff L/D increments for PRA; including aeroelastic effects. Deltas relative to Baseline Aileron Deflection (7.5°).

In addition to possible L/D improvement, potentially significant improvements in $C_{L,max}$ are predicted in the CFD study in the takeoff configuration with modeled flow control at the pylon/wing junction. CFD predicts 4% and higher increases in $C_{L,max}$ at higher PRs (final report document #2 [8]). It is likely that relevant $C_{L,max}$ improvements can remain for the PRA configuration after including trim and aeroelastic effects.

Furthermore, based on the CFD results for the takeoff configuration, it is anticipated that relevant $C_{L,max}$ opportunities exist for the landing configuration (with gapped slats and deeper flap deflection). Future AFC integration studies are needed to quantify net aerodynamic benefits for flow control opportunities in the nacelle/pylon/wing region.

2.4 AFC Structural Weight Increments on Performance Reference Aircraft

For purpose of current conceptual integration and trade study, the AFC effect of increased loading associated with flow control on structural weight was estimated using conceptual-design trades to account for changes in wing-root-bending-moment on the PRA wing (under baseline load-alleviation assumptions).

The approximate analysis approach is appropriate for scoping of various wing AFC concepts. Further investigations of wing AFC applications should include structural FEM/Loads/Weight sizing studies based on detailed CFD loading increments. The estimated structural weight penalty is included in the AFC performance assessment. Estimation of incremental systems' weights associated with additional hardware to supply mass flow to the AFC actuators is estimated in Section 3 of this report.

2.4.1 Aileron AFC - Structural Weight Increments

Figure 10 summarizes the estimated weight increment to account for wing loading changes due to deeper aileron deflections equipped with AFC, relative to the baseline PRA configuration. The spanload changes associated with aileron AFC deflections (see final report document #2 [8]) and resulting increases in Wing-Root-Bending Moment, result in additional structural material (weight) to accommodate the increased loading with AFC. For AFC applied to aileron deflections of 16°, structural weight increases is on the order of 0.2 - 0.35% OEW depending on PR. Relatively significant further increase in OEW structural weight penalty would occur for AFC aileron deflections over 16° - even though net aerodynamic L/D benefit does not increase (see earlier Section).

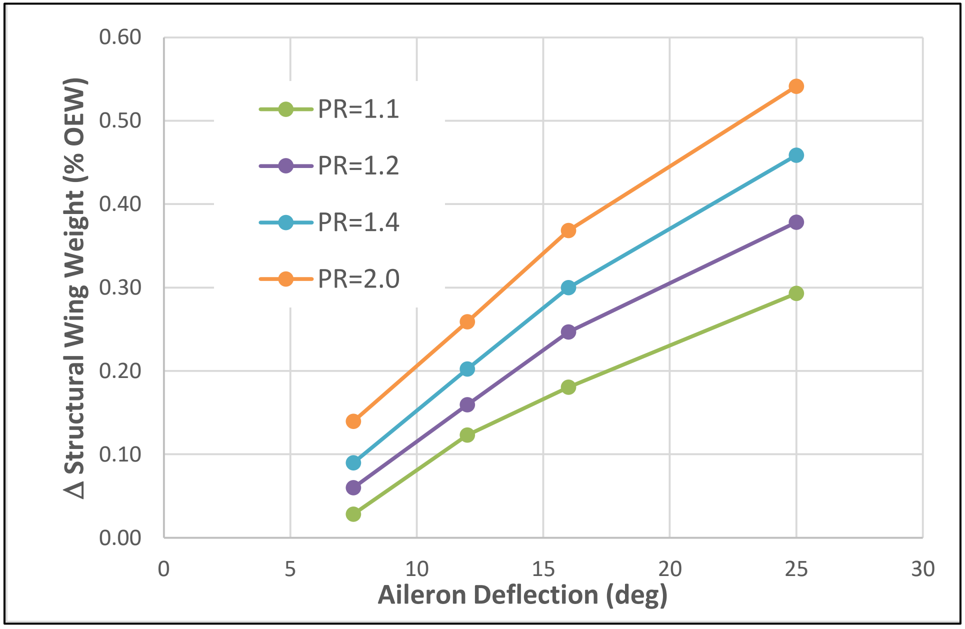

Figure 10 – Aileron AFC: Structural weight increment for modified takeoff wing loading with AFC. Deltas relative to baseline aileron deflection (7.5°).

2.4.2 Wing Leading Edge AFC - Structural Weight Increments

2.4.2.1 Outboard Slat Region – Takeoff

Figure 11 summarizes used structural weight increases for AFC application to the wing outboard region near Slat #1. Wing leading edge AFC application has a smaller estimated weight impact than aileron application in view of reduced WRBM loading. Structural weight penalty is ~0.05 – 0.15% of OEW for PRA.

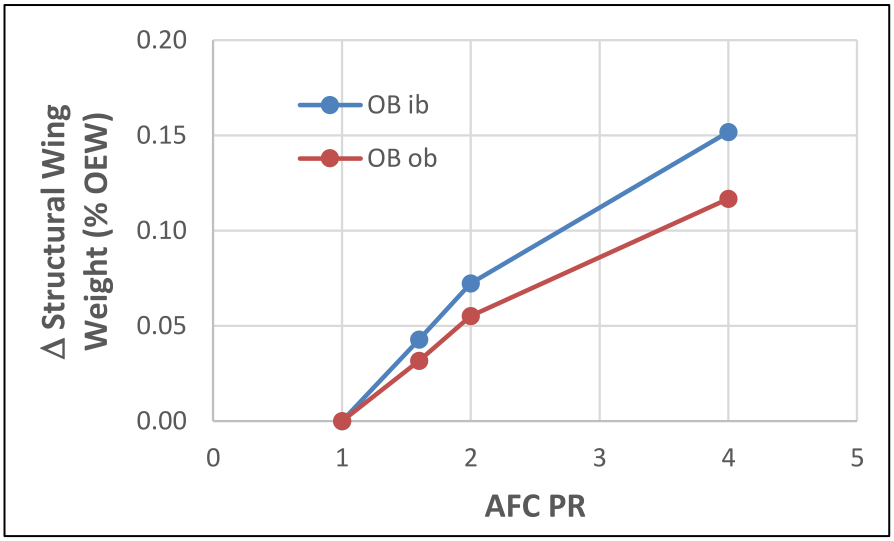

Figure 11 – AFC in Outboard Slat Region: Structural Weight Increment for modified takeoff wing loading with AFC. Deltas relative to Baseline Aileron Deflection (7.5°).

2.4.2.2 Nacelle/Pylon/Wing Junction Region – Takeoff

Figure 12 summarizes used structural weight increases for AFC application to the nacelle/pylon/wing junction region. AFC application at this condition has the smallest estimated weight impact of the AFC cases considered in current study – less than ~0.05% OEW.

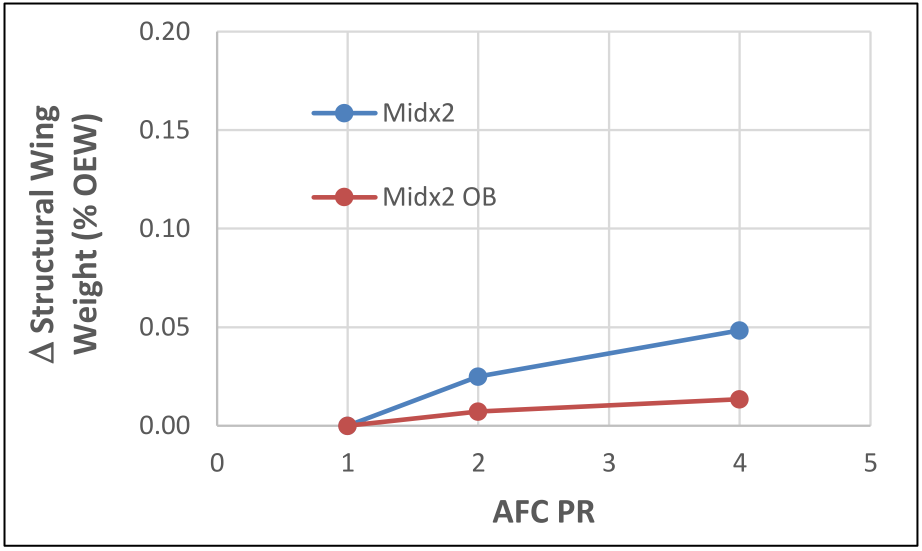

Figure 12 – AFC in Nacelle/Pylon/Wing Region: Structural Weight Increment for modified takeoff wing loading with AFC. Deltas relative to Baseline Aileron Deflection (7.5°).

3 AFC Energy Systems and Integration

Multiple sources of flow to the AFC actuators were studied to assess the potential performance benefit and airplane impacts associated with each. The best AFC flow source is one that provides flow at a sufficiently high pressure and flow rate to maximize the aerodynamic benefits while minimizing weight and complexity increases to the baseline airplane. Since this is a scoping study, the objective was to evaluate a range of AFC configuration options and determine the airplane level effect of each. The aerodynamic benefit from each flow source can then be derived by comparing its achievable pressure ratio and flow rate to the CFD analysis at the corresponding pressure and flow rate for a given AFC actuator configuration.

This Section addresses various energy sources for aileron and wing LE AFC applications. Conceptual routing and associated installation and weight impacts are estimated for each of the AFC areas. Availability/reliability aspects of AFC energy sources and system components were studied only qualitatively with considerations of redundancy. Finally, a summary assessment of energy systems considered is provided.

3.1 Energy Systems for Wing AFC

3.1.1 Energy Sources on Aircraft Studied for AFC Application

Using aileron AFC application as an example, a summary is given of main existing and new energy sources for the reference configuration that may be considered for AFC actuation during takeoff and initial climb, and/or during final descent and landing phases.

Table 1 provides a comparison of approximate feasible mass flow and PRs available from these three potential AFC energy sources relative to AFC requirements for the studied applications. The available mass flow is expressed as a percentage of a near-maximum reference APU mass flow rate representative of APU applicable for a PRA configuration.

Table 1 – Potential Energy Sources vs. Approximate Wing AFC Requirements (Sea-Level).

AFC Flow Source	Flow Rate per Airplane (A/P) (% Max APU Flow)	Pressure Ratio (PR)	AFC Req (A/P) Aileron (% Max APU Flow)(@ PR)	AFC Req (A/P) OB Wing Slat (% Max APU Flow) (@ PR)	AFC Req (A/P) Nacelle-Pylon (% Max APU Flow) (@ PR)
APU Load Compressor	100	2.9 - 3.9	30-63 (@1.4 – 2)	38-63 (@ 1.6 – 4)	25-50 (@ 2 – 4)
Electric Compressor	38	2.0 - 2.3	30-63 (@1.4 – 2)	38-63 (@ 1.6 – 4)	25-50 (@ 2 – 4)
Engine Bleed (both engines)	30-40	3.0 - 4.0	30-63 (@1.4 – 2)	38-63 (@ 1.6 – 4)	25-50 (@ 2 – 4)

As will be discussed in greater detail below, generally the APU load compressor can provide required mass flow and PR (assumes that the APU is running). Engine bleed could provide adequate flow with pneumatic flow management of other systems (WAI, EAI, A/C packs). A combinations of bleed and APU air may provide increased availability for AFC. Electrical compressors are typically limited in PR (otherwise requiring cooling), are relative heavy, and need a source for electrical power (engine generator, battery).

Following are the AFC energy-source configurations considered in this Section:

- Configuration 1: APU Load Compressor to Aileron AFC
- Configuration 2: Electrical Compressor(s) to Aileron AFC
- Configuration 3: APU Load Compressor/ Engine Bleed to Nacelle/Pylon/Wing AFC

3.1.2 Configuration 1: APU Load Compressor for Aileron AFC

3.1.2.1 Conceptual Integration of APU System Routing

This configuration takes air from the APU load compressor to power AFC actuators in the fixed trailing edge of the wing along the aileron location as shown in Figure 13. The APU would operate during takeoff / landing to supply AFC actuators for conditions requiring increased L/D and/or $C_{L,max}$. The APU is capable of providing mass flow at pressure ratios PR up to 3 – 4 at the aileron station.

An AFC supply duct branches off of the main APU duct upstream of the environmental control system cross-over duct and is routed into the wing trailing edge. The supply duct terminates at the aileron where the flow is routed to the AFC actuators, which are embedded in the fixed trailing edge of the wing.

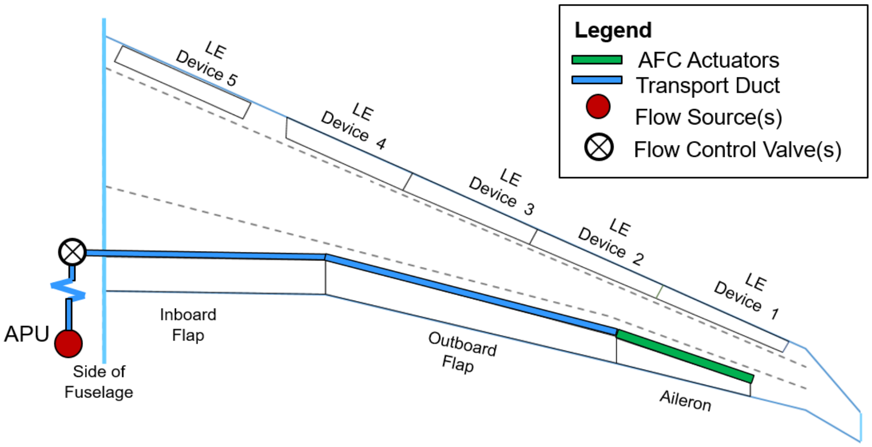

Figure 13 – Aileron AFC: Conceptual Systems Routing from APU to Aileron.

Use of APU during takeoffs and landings will likely result in increased maintenance needs for the APU. It is noted that APU on existing aircraft can be operated in flight to supplement pneumatic and/or electrical energy to the aircraft systems when needed (e.g., in engine-out operations). Further detailed study is required, but meeting AFC system reliability requirements appear feasible with this configuration – in view of failure rates of APU relative to probability of engine out in takeoff.

The weight of the APU and the main pneumatic duct through the fuselage to the A/C pack area near the wing intersection with the fuselage is already accounted for in the baseline airplane weight rollup, minimizing the weight penalty of this AFC configuration. To provide flow to the AFC actuators in the ailerons, a separate AFC supply duct would split off from the main APU duct and be routed into the wing's trailing edge where it would provide flow to the AFC actuators at the ailerons.

The schematic for the APU-Aileron AFC configuration is shown in Figure 14. The additional isolation valve is placed such that the pneumatic system retains the ability to perform its normal operational duties while the APU is supplying flow to the AFC actuators. A parallel AFC valve configuration is conservatively shown to allow for AFC operation in the event that the primary AFC valve fails. This requires that the AFC valves be designed such that they fail in the closed position. This layout ensures that both the left and right wing AFC actuators receive equal supply pressure and flow rates since either the primary or backup AFC valve is providing flow to both sides simultaneously. Asymmetric aerodynamic performance can pose a hazard to safe flight so an AFC system should be designed to minimize that possibility. Pressure sensors in the left and right wing can be used to monitor and regulate flow in the AFC supply ducts to ensure that both sides are receiving equal amounts of flow.

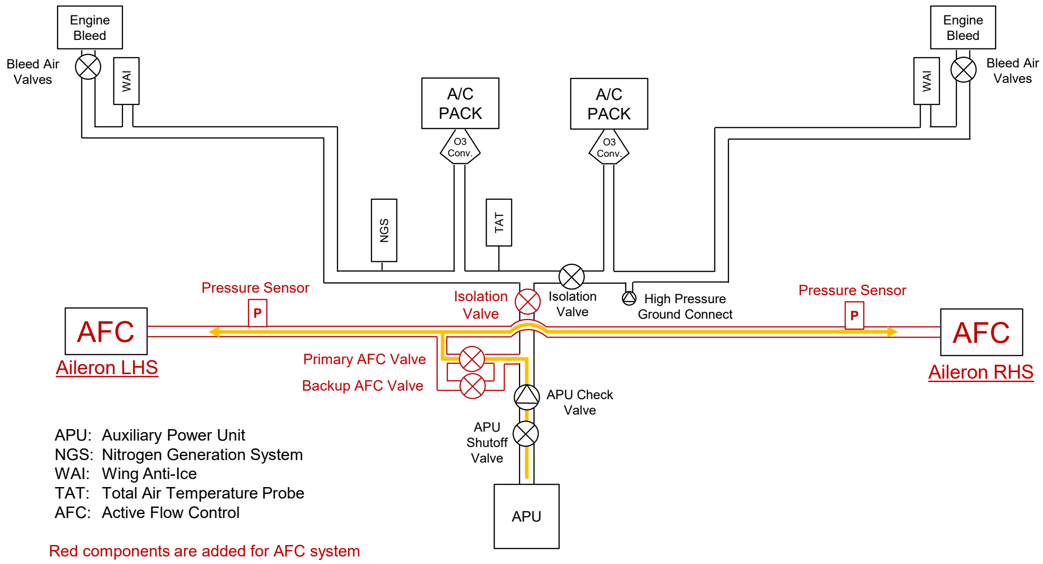

Figure 14 – Aileron AFC: Conceptual Systems Integration of APU routing in Baseline Pneumatic Systems.

This would require the addition of at least two valves; one shutoff valve to control flow to the AFC actuators in the left and right wings, and one additional isolation valve downstream of the AFC duct branch but upstream of the ECS cross-over duct to prevent the APU air from flowing against the engine bleed air. To improve the availability and reliability of the AFC system, a second AFC shutoff valve is assumed in parallel with the first (as shown in Figure 14). If the primary valve fails in the closed position, the second valve (normally closed) could open to provide flow to the AFC actuators.

When using the APU to provide flow to the AFC system, the APU air must be kept isolated from the engine bleed air in order to prevent flow reversal into the engine from the APU or vice versa as this could cause an engine or APU stall or surge. The added isolation valve serves this purpose. Valve location is important to ensure that the APU can still provide flow to the AFC actuators in the case of a single-engine or single-bleed scenario.

3.1.2.2 APU System Layout Considerations

Figure 15 shows a planform view of the wing with a nominal path for the aileron AFC supply duct. Additionally, it shows the approximate location of the AFC actuators overlaid against the wing structure and aileron flight control actuators. The cross-section in Figure 16 shows how challenging it would be to maneuver the AFC supply duct around the flight control actuators and that incorporating AFC actuators at that section of the aileron is most likely not a possibility which may result in somewhat lower aerodynamic performance benefits than was achieved in the CFD analysis. It may be necessary to route the duct through a wing rib in order to provide flow to the section of aileron outboard of the flight control actuators. This is not an ideal structural configuration and needs to be assessed in detail to ensure feasibility. Further work should be done to determine if it is possible to move the flight control actuators to the outboard-most location of the aileron so the AFC duct would not need to move around them. This would allow for easier integration of the AFC duct and AFC actuators.

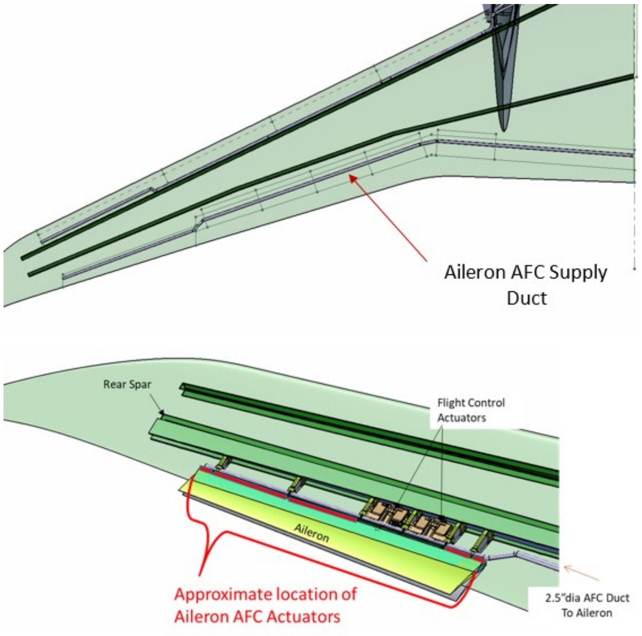

Figure 15 – Conceptual integration of AFC supply duct from fuselage to aileron.

Figure 16 shows the conceptual AFC actuator profile embedded in the fixed trailing edge of the wing at the aileron hingeline. This particular actuator is representative of the ‘50% nozzle’ used in the CFD analysis as scaled to the PRA configuration.

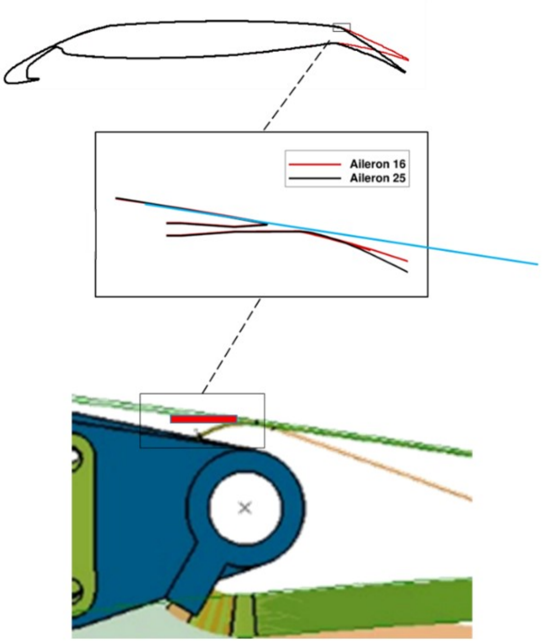

Figure 16 – Cross-section of the aileron hinge region with AFC actuator at the upper-surface aileron leading edge.

Figure 17 displays the cross-sectional view of the AFC duct integrated into the fixed trailing edge of the wing. In the spanwise region with flight control actuators, it is challenging to route the AFC duct near the aileron hingeline. An alternate location behind the rear spar with chordwise smaller ducts may be required to achieve a feasible integration solution. Application of AFC in the aileron region may be relatively easier on aircraft larger than the current performance reference configuration.

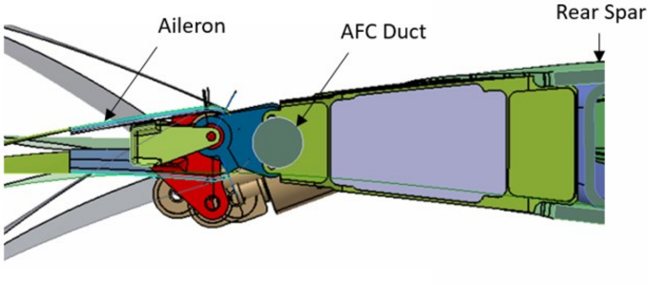

Figure 17 – Cross-Section near aileron hinge on study configuration with conceptual AFC duct.

3.1.2.3 APU AFC Flows, AFC Duct Sizing and AFC Systems Weight

Using the APU as the source of flow to the AFC system is attractive for several reasons. For scenarios where the AFC performance is required during the takeoff or climb flight phase, the full capability of the APU is available since it is not typically otherwise used for any other systems during that flight phase. Contrast this to bleed air from the engine, which penalizes engine performance during takeoff when the engines are operating at full power. The engines are highly optimized and any thrust loss during takeoff may result in the inability to meet takeoff performance requirements and objectives.

The achievable pressure and flow rates coming from the APU for an aircraft in the size class of the performance reference aircraft are higher than those that could reasonably be achieved from an electric compressor. Specifically, at sea level and ECS hot day conditions, sufficient flow can be provided by the APU load compressor at pressure ratios up to between 2.5 and 3.9.

The flow rates available from the APU will decrease as altitude increases due to the natural decline in air density with increasing altitude. However, the pressure ratio from the APU will remain high.

An advantage of the APU as a flow source is its ability to provide pressure ratios in the range of 3 - 4 at altitude up to the highest takeoff and landing fields while still providing sufficient flow rates to provide flow rates and pressures to achieve significant L/D and $C_{L,max}$ improvements as described in Section 2.

Preliminary-design methods and applicable integration assumptions were used to estimate conceptual systems weight increments associated with providing APU flow to the aileron AFC actuators. The resulting estimated systems weight increase for APU supplied AFC flow ranges from 0.09 – 0.13% OEW.

3.1.2.4 APU System Operational Considerations

This configuration is intended to provide enhanced takeoff and climb performance by increasing L/D of the airplane during takeoff. Required takeoff L/D is determined largely by the scenario of an engine failure during a critical takeoff speed. If credit is to be taken for the aerodynamic performance benefit of this AFC configuration with regard to the required takeoff thrust of the engines and subsequent cascading weight impact, the AFC system must have availability and reliability in alignment with the hazard classification of this failure event.

For takeoff scenarios where flight safety and performance require the aerodynamic benefit that the AFC system provides, the operator must be confident that the system is operating normally at takeoff. A high level use case of this configuration is as follows:

1. The operator turns on the APU prior to takeoff to ensure that it is operating normally and providing flow to the AFC actuators.
2. The APU, AFC valves, and sensors perform a self-diagnostic test to verify that all components are functioning normally.
3. The airplane takes off with the system providing flow to the AFC actuators.

4. In the event of an engine failure at a critical takeoff speed, the AFC system is already operational prior to the failure and providing the capability to maintain sufficient aerodynamic performance to ensure continued safe flight and landing in the event of an engine failure.

For configurations providing AFC during approach/landing:

1. The operator activates the AFC system prior to the start of the approach phase. This opens the primary AFC valve.
2. A system diagnostic is automatically performed to ensure the system is functioning properly. If the system is faulty, a backup flow source or valve may be used depending on the configuration.
3. The operator enters the approach and landing phase while the AFC system is operating. Meanwhile, the system continuously monitors the pressure downstream of the AFC valve to ensure that it is operating normally.

3.1.2.5 APU Availability and Reliability Considerations

The probability of an engine failure with a simultaneous failure of the AFC system at the critical takeoff speed must be commensurate with the hazard classification of that event. A hazardous event must have an occurrence rate on the order of 10^{-7} per flight hour while a catastrophic event must have an occurrence rate on the order of 10^{-9} per flight hour or less. By turning on the APU prior to takeoff, the flight crew can be assured that it is running during the initial takeoff phase of flight where it is most needed. Assuming 6 minutes for the takeoff flight phase, with an engine failure rate of 1 occurrence per 100,000 flight hours, the probability of either engine failing during takeoff is 2×10^{-6} per flight hour multiplied by the time duration of takeoff. Assuming a failure of the AFC combined with an engine failure during takeoff is catastrophic, the AFC system failure rate should be on the order of 5×10^{-4} per flight hour or better. The valves, controller, sensors, ducts, and actuators must therefore provide sufficient reliability to meet this requirement [9].

Regarding the use of the APU to power AFC, there are reliability challenges concerning the APU's ability to restart while in-flight. The APU's typical in-flight restart reliability of around 99.5% is of potential concern if AFC aerodynamic benefits are required to provide adequate landing performance. However, in cases where the APU fails to start during the latter phase of descent (i.e., well before the final approach where AFC would be required), landing speeds may need to be adjusted to compensate for loss in $C_{L,max}$ or margin to tail clearance at approach angle of attack. For airports with limiting landing field lengths, an in-flight diversion could be required if landing speeds are increased to the point that the airplane cannot safely meet the landing field length of its target destination. Depending on the expected size and range of the airplane, as few as 1% of missions may be landing field length limited making the probability of an APU start failure resulting in a diversion on the order of 5×10^{-5} or better. This could be potentially be mitigated by leaving the APU on for the duration of a flight – albeit at a penalty of increased fuel burn [9].

Another option for AFC use during landing if the APU does not restart would be to employ the use of engine bleed as the AFC flow source. Unless there is a simultaneous failure of one engine's bleed system, there should be sufficient engine bleed available during approach and landing to supply the AFC system. Engine bleed as an AFC flow source is discussed in Section 3.1.4.

For current conceptual scoping, it appears that system availability requirements for certification can likely be achieved with appropriate mission planning. At this point, it is uncertain how increased use of the APU on takeoff would affect its failure rate, if at all. APU maintenance can be expected to slightly increase to mitigate this. Any follow-on studies would need to further explore APU availability, and quantify possible additional APU maintenance and inspection requirements.

3.1.2.6 Engine Bleed as Backup to AFC Flow Source

Given that AFC at the ailerons requires a relatively small amount of mass flow to provide a significant aerodynamic benefit, a potential option to improve the redundancy and availability of the AFC system is to use engine bleed air as a backup flow source. This would only be applied in the unlikely event of a single engine failure combined with an in-flight failure of the APU at a critical takeoff or landing speed. This would require detailed analysis to determine if the engine can provide the required flow to the AFC actuators while still producing sufficient thrust to maintain safe operation and control of the aircraft in an emergency engine-loss scenario during a critical takeoff phase. Management of the pneumatic bleed air users could provide a solution to this problem. If the performance that the AFC system provides is only required for a short duration, less than 30 seconds for example, then flow to the A/C packs could be significantly reduced in an emergency during this transient period to limit the total bleed extraction from the engines during this time in order to maintain thrust production from the one engine that is still operating. This contingency would not be required if it can be shown that the probability of a simultaneous engine failure and AFC system failure is less than 10^{-9}/flight hour.

3.1.2.7 Summary Considerations on APU as Energy Source for Aileron AFC

- APU operates during takeoff to supply AFC actuators when conditions in takeoff configuration require increased L/D, and during landing to improve $C_{L,max}$ ($C_{L,app}$) if needed.
- APU can provide energy supply to support aileron AFC (mass flow and PR).
- Additional weight increase for APU powered AFC aileron system is up to 0.125% OEW.
- Effect of increased use of APU must be accounted for in reliability assessments. System availability requirements for certification can probably be achieved (additional detailed FHA analyses would be needed through mission planning.
- Integration of AFC duct in aileron region is challenging for smaller aircraft, but can probably be achieved. Spatial integration challenges is mitigated if flight control actuators can be moved or separated in spanwise direction.

3.1.3 Configuration 2: Electric Compressor(s) for Aileron AFC

Alternate AFC energy source configurations considered using electrically driven centrifugal compressor(s) to provide pneumatic flow to AFC actuators to the ailerons during takeoff or approach/landing. Three variations of this concept were evaluated in the current scoping study to assess feasibility.

The first variation (Configuration 2a) critically assumes that the airplane's environmental control system is of similar architecture to an existing configuration where cabin air is provided through electric cabin air compressors. These compressors would then serve a secondary purpose of providing flow to the AFC actuators as the AFC system could tap flow from those compressors during takeoff and approach/landing. If an electric ECS architecture is the baseline configuration for an airplane then the weight and integration penalty of using those compressors to provide flow to the AFC actuators is minimal compared to using a dedicated AFC compressor. If a future single-aisle airplane uses an electric air supply system with such all-electric ECS architecture, then there would be redundant compressors available to supply the AFC actuators in the event that one compressor failed.

The second configuration (2b) uses electric compressors powered by the airplane generators to power the AFC system but it assumes that the airplane is a traditional ECS configuration whose bleed flow is provided by pneumatic engine bleed-air. The dedicated AFC compressor(s) are assumed here to be located in or near the A/C pack bay of the aircraft with outlet ducts providing flow to both wings. This configuration results in a significant weight increase over a baseline airplane configuration due to the additional electrical equipment required to power the compressor.

The third configuration (2c) is the same as the second configuration with the exception that the AFC compressors are powered by 270V lithium-ion batteries. Since the AFC system is intended to be used during takeoff or approach/landing, the battery power would only be required for short durations and could be recharged during the cruise portion of flight.

Regardless of the configuration, the compressor is assumed to be a motor driven centrifugal compressor, which is supplied by outside air ducted from a ram inlet to the compressor inlet. Information on existing cabin air compressors along with handbook methods provided the basis of weight, pressure, flow rate, and power requirement estimates.

Preliminary-design methods and related integration assumptions were used to define systems details for studied electrical-compressor options to drive AFC. The main analysis result is that electrical compressors will add significant weight to the aircraft and with a maximum feasible pressure ratio at the AFC actuators of about 2.0. Higher pressure ratios at the AFC ports increases the aerodynamic AFC benefit (for given AFC mass flow) but are not practical with electric compressors. This is limited by sea level, hot day conditions so at higher altitudes and lower ambient temperatures, higher pressure ratios may be achievable.

The major challenge of adding an electric compressor is the added weight for electric motor and compressor, the potential need for cooling, as well as potential increase of engine generators to provide the electrical power. The systems weight increase over the baseline airplane ranges from a low of about 0.125% OEWs to as much as 0.52% OEW depending on the compressor architecture and the baseline ECS configuration.

3.1.3.1 Compressor System Operational Considerations

This configuration is intended to provide enhanced takeoff and climb performance by increasing L/D of the airplane during takeoff and approach/landing via AFC actuators in the fixed trailing edge forward of the ailerons.

For takeoff scenarios where flight safety and performance require the aerodynamic benefit that the AFC system provides, system operation may be as follows:

Configuration 2a

1. The operator turns on the cabin air compressors prior to takeoff to ensure that they are operating normally.
2. The AFC system components perform a self-diagnostic test to verify that all components are functioning normally.
3. The AFC valve opens to provide flow to the AFC actuators prior to initiating the takeoff sequence. The pack valves regulate to ensure sufficient flow and pressure is provided to the AFC actuators. System checks again confirm normal operation.
4. The airplane takes off with the system providing flow to the AFC actuators.
5. In the event of an engine failure at a critical takeoff speed, the AFC system is already operational prior to the failure and providing the capability to maintain sufficient aerodynamic performance to ensure continued safe flight and landing in the event an engine failure.

If a cabin air compressor fails to start, then an MMEL dispatch is most likely still available since each aircraft has 4 cabin air compressors. As seen in the system schematic for configuration 2a, any one of them is capable of providing flow to the AFC actuators.

System operation for configuration 2a and 2b will be very similar.

1. The operator turns on the dedicated AFC compressor prior to takeoff to ensure that it is operating normally.
2. The AFC system components perform a self-diagnostic test to verify that all components are functioning normally.
3. The AFC valve opens to provide flow to the AFC actuators prior to initiating the takeoff sequence. System checks again confirm normal operation.
4. The airplane takes off with the system providing flow to the AFC actuators.
5. In the event of an engine failure at a critical takeoff speed, the AFC system is already operational prior to the failure and providing the capability to maintain sufficient aerodynamic performance to ensure continued safe flight and landing in the event an engine failure.

Configurations 2b and 2c assumes a single AFC compressor. Therefore, if it fails, an MMEL dispatch at a takeoff condition, configuration, or field length that requires the use of AFC is not achievable.

For landing scenarios that are field length limited where the AFC system is required in order to meet approach speed requirements, a high level use case of this configuration is as follows:

1 The operator turns on the compressor prior to approach to ensure that it is operating normally and providing flow to the AFC actuators.
2 The APU, AFC valves, and sensors perform a self-diagnostic test to verify that all components are functioning normally.
3 The AFC valves open to provide flow to the AFC actuators in the fixed leading edge.
4 The approach speed required for the target airport is achieved with the added lift performance that the AFC system provides.

For configurations 2b and 2c, in the event that the compressor fails to start or there is another failure of the AFC system, the airplane may need to divert to an alternate airport for landing. Configuration 2a can rely on the other cabin air compressors to provide AFC flow.

3.1.3.2 Pneumatic System Architecture with Electrical Compressors

The system schematic for electrical-compressor configurations 2a and 2b/c studied are shown in Figures 18 and 19, respectively.

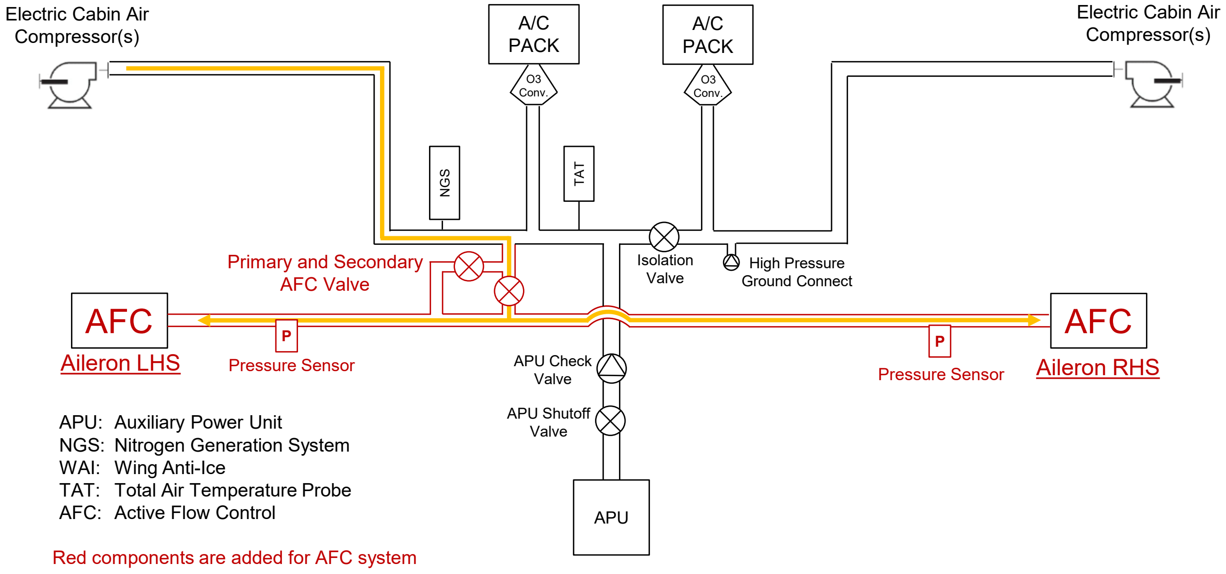

Figure 18 – Aileron AFC – Conceptual Systems Routing from electric Cabin Air Compressors to Aileron.

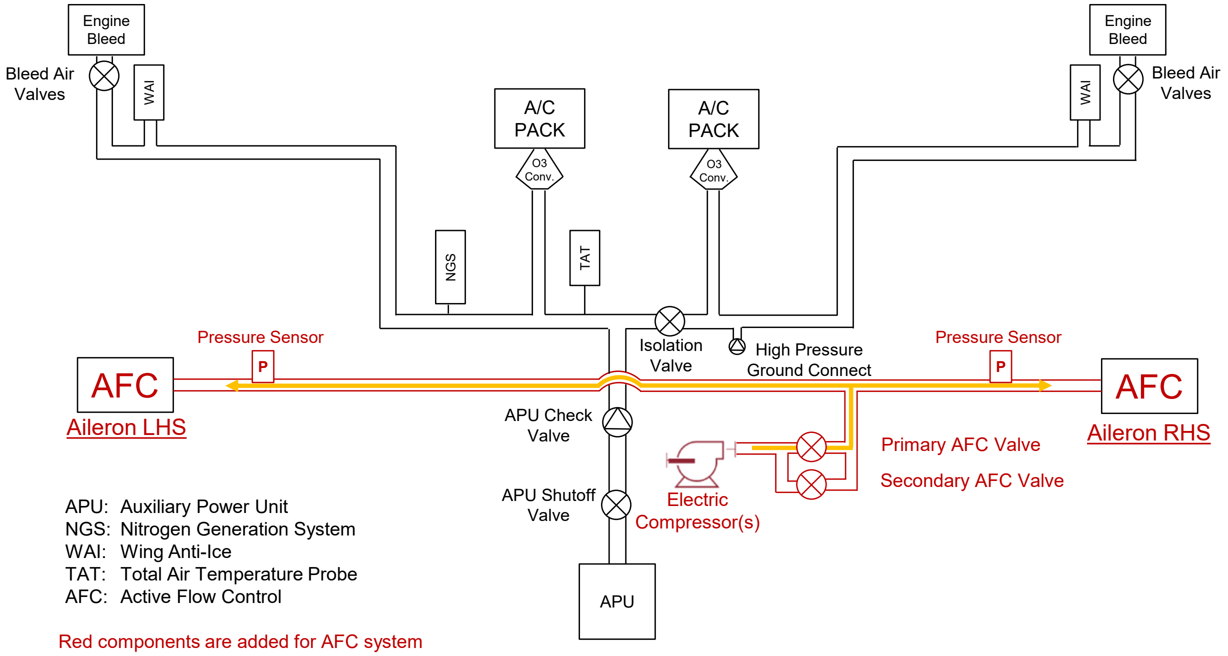

Figure 19 – Aileron AFC – Conceptual Systems Routing from dedicated AFC Compressors to Aileron.

3.1.3.3 Electric Compressor Flow Properties

Electric compressor flow properties studied are summarized here. Assuming that a cabin air compressor on a future midsized aircraft would perform similarly to existing cabin air compressors, a pressure ratio of approximately 2.0 – 2.3 is achievable with flow rates of approximately 40% of maximum APU flow at sea level, hot day conditions. The flow properties of the compressor are limited by its ability to cool itself.

Handbook-type calculations indicate that it requires approximately 70 KW to power an electric compressor that provides a pressure ratio of 2.3 at a flow rate of 40% of maximum APU flow. This assumes a compressor efficiency comparable to other electrical compressors used in the aerospace industry. This is considered the upper limit of compressor performance at sea level hot day conditions in the absence of a more advanced cooling system. The CFD analysis performed on the Performance Reference Aircraft indicate that this is sufficient flow and pressure to achieve the performance benefits specified in Section 2. Significant performance benefits can be achieved with compressors of 50 KW or less providing 28% of the max APU of flow at a compressor outlet pressure ratio of 2.2.

3.1.3.4 Compressor System Availability and Reliability

The same requirements for the AFC system regarding system reliability apply for this configuration as were described for the APU powered AFC configuration.

Configuration 2a will have the highest system availability given the fact that an airplane that is pressurized via cabin air compressors will have multiple compressors that can be used to power the AFC system in the event that one fails. Similarly to the APU concept for configurations 2a – 2c the operator will know if the system if functioning properly immediately prior to takeoff since the system will perform a built-in test evaluation immediately before it is used. This limits the window of time for an unexpected failure to occur to a very small period. This helps to achieve the level of reliability that is commensurate with a system, which, if it were to fail, can result in a significant hazard to the airplane. Reliability of other system components such as valves, pressure sensors, and ducts must be considered in determining the necessary reliability of the compressors and overall system.

3.1.3.5 AFC Systems Weight with Electrical Compressor(s)

The following is a summary of estimated AFC weight impacts:

Configuration 2a: Electric ECS – AFC uses air from existing CAC: 0.12 – 0.15% OEW

Configuration 2b: Bleed-Air ECS – Dedicated generator powered AFC compressor: 0.27- 0.51% OEW
Configuration 2c: Bleed-Air ECS – Dedicated battery powered AFC compressor: 0.33 – 48% OEW.

The reader is reminded that the weight impact of the AFC system in configuration 2a is less than that of configuration 2b and 2c is due to the fact that weight of the cabin air compressors and other electrical equipment necessary for is already accounted for in weight of the baseline airplane for configuration 2a.

3.1.3.6 Summary Considerations on Electrical Compressors as Energy Source for Aileron AFC

The compressor sizing and its maximum output pressure capabilities assumed that compressor technology has not much improved relative to existing cabin air compressors. This is likely valid for this study since the cooling system is considered a limiting factor and enhanced cooling systems to achieve higher pressure ratios will require additional weight. Higher pressure ratios at the AFC ports can increase the aerodynamic benefit according to CFD analysis (as well as reduce duct size) but it is probably not feasible with electric compressors. This is limited by sea level, hot day conditions so at higher altitudes and lower ambient temperatures, higher pressure ratios may be achievable.

The major shortfall of adding electric compressor(s) considered is the significant addition of AFC related weight. The equivalent weight benefit of the improved takeoff L/D must be high enough to overcome the significant actual weight liability of the compressors.

In summary, estimated systems weight increase over baseline airplane ranges from 0.12 – 0.50% OEW depending on the compressor architecture and the baseline ECS configuration. If the baseline ECS system already utilized electrical cabin air compressors, configuration 2a could provide high levels of compressor flow availability with low incremental systems weight penalty.

3.1.4 Configuration 3: APU and Engine Bleed-Air for Nacelle/Pylon/Wing Region AFC

This AFC configuration is designed to provide AFC actuation at the engine pylon location of the wing fixed leading edge to improve takeoff or landing performance by increasing $C_{L,max}$ and/or takeoff L/D. One or two spanwise AFC actuators are embedded in the fixed leading edge on either side of the engine pylon (see Figures 20 through 22). The APU can plausibly be used to provide AFC air during takeoff and engine bleed can be used during approach and landing. Furthermore, this configuration provides built-in redundancy in that bleed-air can be used as a backup flow source in the event that the APU fails or vice versa.

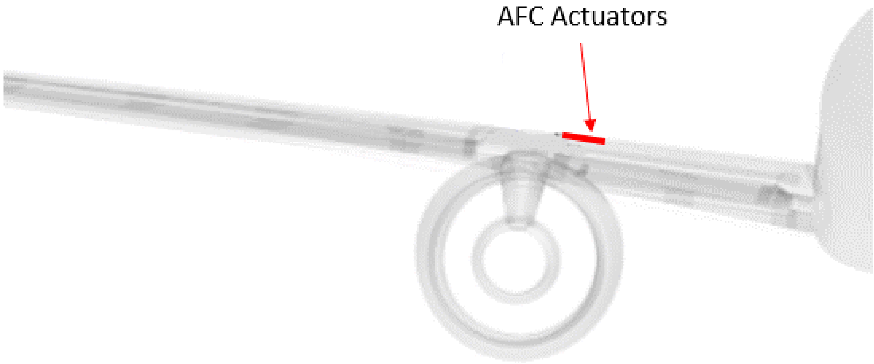

Figure 20 – Nacelle/Pylon/Wing AFC actuator location (inboard actuator shown).

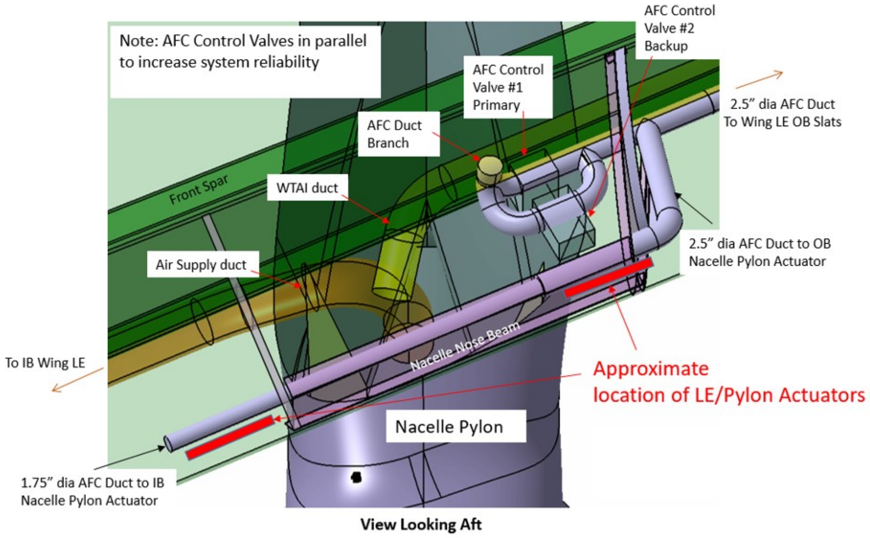

Figure 21 – Schematic duct, valves, and AFC actuator integration near nacelle/pylon/wing junction leading edge.

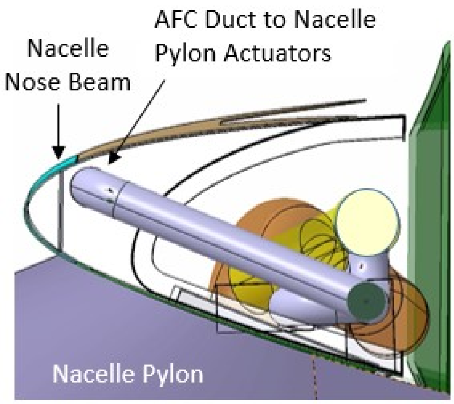

Figure 22 – Wing LE Cross Section at Nacelle/Pylon/Wing Junction (view looking IB).

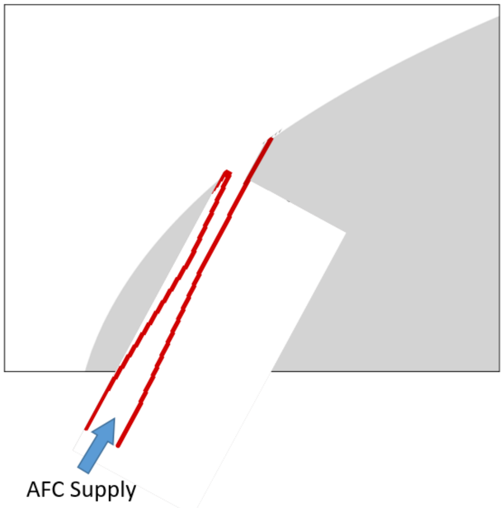

Figure 23 – Notional AFC actuator in Wing Leading Edge.

The APU or engine bleed-air can be used to provide flow to the AFC actuators in the fixed leading edge and the main ECS duct may be used to transport this flow from the ECS area in the fuselage to the nacelle/pylon regions. This is a highly efficient configuration since there is only a very short amount of new ducting required due to the close proximity of the ECS main duct to the AFC actuators in this configuration. This duct is already used to transport air from the APU to the main engine starter and the AFC actuators are near the existing supply duct. The duct layout of this configuration is shown in Figure 21. Figure 23 provides a notional geometry of an AFC actuator in leading edge region (i.e., a converging-diverging AFC actuator nozzle is assumed). Figure 24 summarizes conceptual systems routing integration in the wing and fuselage to supply AFC flow from engine bleed and/or APU sources to the nacelle/pylon/wing juncture region.

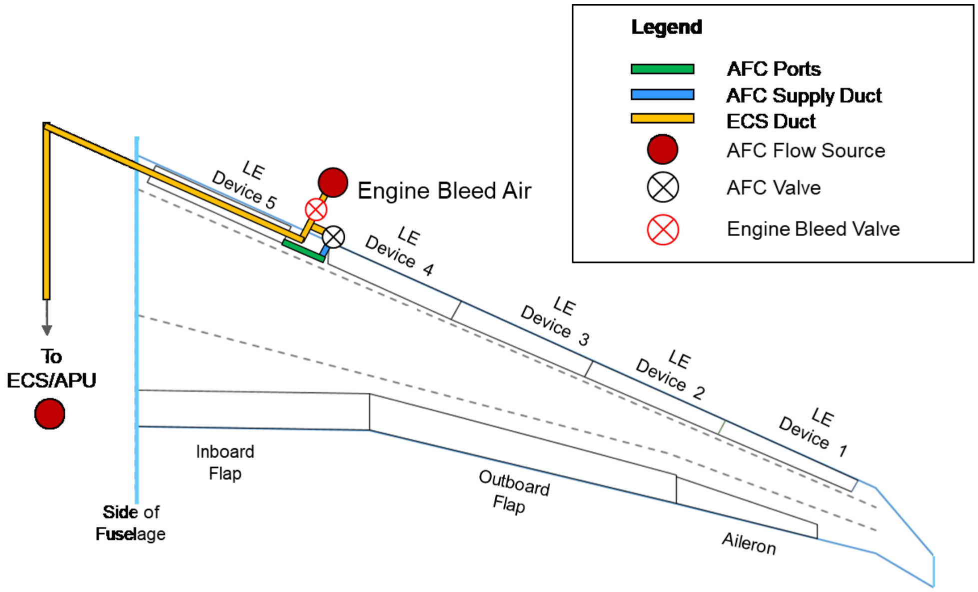

Figure 24 – Nacelle/pylon/wing juncture AFC: Conceptual Systems Routing from Bleed and/or APU.

3.1.4.1 System Operational Considerations

Similar to configurations 1 and 2, current configuration 3 is intended to provide enhanced takeoff and climb performance by increasing L/D and $C_{L,max}$ of the airplane during takeoff.

For takeoff scenarios where the AFC system is required, a high level use case of this configuration is as follows:

1. The operator turns on the APU prior to takeoff or leaves it running following the engine start sequence to ensure that it is operating normally and providing flow to the AFC actuators.
2. The APU, AFC valves, and sensors perform a self-diagnostic test to verify that all components are functioning normally.
3. Engine bleed, NGS, WAI, and A/C pack valves close prior to AFC system activation. If the APU is used to provide flow to the NGS or A/C packs, then these valves remain open.
4. The airplane takes off with the system providing flow to the AFC actuators.
5. In the event of an engine failure at a critical takeoff speed, the AFC system is already running and providing the capability to maintain sufficient aerodynamic performance to maintain continued safe flight and landing in the event an engine failure. In the event of an APU failure while the AFC system is required, the isolation valve can open to allow engine bleed from the functioning engine to power the AFC actuators to maintain performance.
6. Once the critical takeoff speed is exceeded, the APU powers down, the AFC isolation valve closes, and normal pneumatic bleed air operation is resumed.

This configuration can also provide enhanced approach and landing performance by increasing L/D and $C_{L,max}$ of the airplane during these phases of flight through the use of either APU or bleed-air. The use case is similar to the use case for takeoff scenarios in that the AFC system should be activated prior to needing them to ensure that the system is functioning properly during the critical period where the system is needed.

3.1.4.2 Pneumatic System Architecture

A notional pneumatic system layout and airflow path is displayed in Figure 25. The APU and engine bleed-air share a common duct allowing engine bleed-air to serve as a backup flow source to the APU or vice versa.

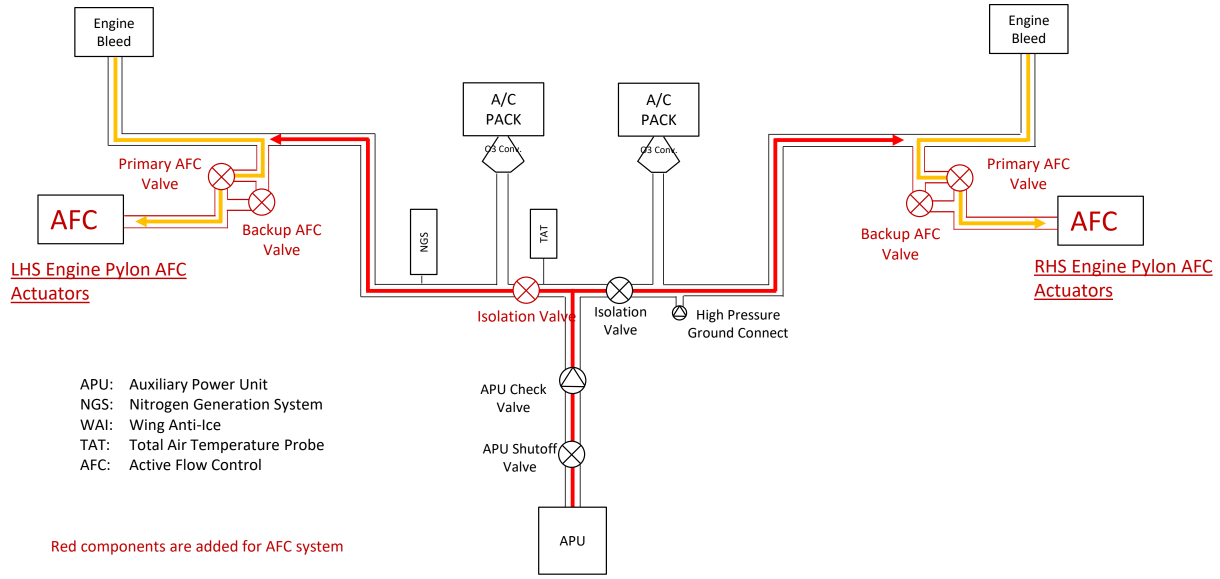

Figure 25 – Leading Edge AFC – Conceptual Systems Routing from APU or Engine Bleed to nacelle/pylon/wing region.

3.1.4.3 Duct, Valve, and AFC Actuator Integration

A notional physical implementation of this system is given in aforementioned figures. From conceptual integration, it appear feasible to incorporate the ducts, valves, and actuators in this leading edge volume. There are still components in this region such as other valves that need to be considered but generally, integration of the AFC actuators closer to the source of the flow is less disruptive to the surrounding structure. Unlike the trailing edge aileron integration, the issue of maneuvering the AFC supply duct around ribs, flight control actuators, and other components is less challenging in this region.

A duct diameter of 2.5” was assumed for integration and weight estimation and volume is available to incorporate such a duct size. The duct between the offtake tee fitting and the AFC actuators is short (~1-2 ft per side) and pressure losses as well as weight reduction would be minimal if a smaller diameter duct was selected.

3.1.4.4 APU Load Compressor - Flow Considerations

The capability of the APU to provide flow is identical in this configuration as in configuration 1. However, the current configuration also explores the flow and pressure available to the AFC actuators if the APU were required to simultaneously provide flow to the A/C packs. The flow rate to the AC packs is nearly 90% of the max APU flow rate for an airplane in this size class when operating at flow schedule 1 (normal operation), which would leave only 10% of the APU’s max flow rate available for the AFC system at sea level hot day conditions. This would likely not be a sufficient amount of flow to achieve a significant aerodynamic benefit.

Current airplanes typically supply the AC packs with bleed air during takeoff unless the takeoff conditions require a thrust level at or near the sizing conditions of the engine, in which case, flow to the packs is reduced. Similarly, for approach/landing conditions, airplanes typically must provide full performance to the packs. There are some takeoff conditions that require thrust at or near the maximum thrust capability of the engine where pack flow is temporarily reduced or shut off. Since there is precedent for this, we continue analysis of this configuration assuming that some reduction in pack flow is allowable for the short duration that the AFC system is required. However, this integration opportunity needs to be validated in future studies.

Further analysis also needs to be performed to determine the exact pressure available to the AFC system if the packs were consuming flow simultaneously but it is likely the case that a configuration exists that provides sufficient flow to both APU flow users given the maximum pressure and flow capabilities of the APU. It is feasible to expect that 25-38% of the maximum APU flow at a pressure ratio of 2.0 to 3.5 will be available if total airplane flow demands can be managed during the phases of flight where the AFC system is needed. These flow rates are adequate to provide aerodynamic AFC improvements for the Performance Reference Aircraft.

3.1.4.5 Engine Bleed – Flow Considerations

Unlike at takeoff conditions, the thrust impact of extracting engine bleed air during landing is not a concern. It is a challenge, however, to ensure that all bleed-air applications receive sufficient flow. Wing anti-ice, engine anti-ice, AC packs, and NGS require specific amounts of bleed air flow during approach and landing in icing conditions, which may make it challenging to provide additional flow to the AFC system simultaneously. The estimated available bleed air for the AFC actuators is shown in Table 2. These values make assumptions regarding the required flow to WAI and EAI and assume that the packs are operating at a specific flow schedule. This is highly dependent on the ice protection requirements of a given configuration. Airplanes that require more wing ice protection span or require a fully evaporative anti-ice system with no allowance for runback ice will have less flow available to the AFC system. The numbers shown below are based on the WAI and EAI flow rates required for an airplane in the size class of the study airplane and are considered to be of moderate fidelity. If an electric WAI system were used, then there would be significantly more flow available to the AFC system.

Table 2 – AFC bleed air assumed available from engine with traditional pneumatic ice protection system.

Altitude (ft)	AFC Bleed Available per Engine (% Max APU Flow)
0	15-20
5000	10-13
10000	5-8
15000	3

During approach and landing bleed air would most likely be extracted from the high pressure port of the engine compressor. This air supply is typically regulated to around 50-55 psig at sea level with a natural decrease in pressure occurring with altitude.

Even a moderately optimistic assessment of the total bleed flow demand of the airplane does not leave a high amount of bleed flow available for the AFC system. As stated already, at some altitudes, clever management of available bleed flow would be required to supply all pneumatic systems from the limited bleed flow supply of the engines. Detailed analysis is required to ensure that a pressure ratio of 2 is available to the AFC actuators while other systems are active. A pressure ratio of 4 is available downstream of the bleed regulation valve so if the AFC system is the only bleed user then a significant $C_{L,max}$ improvement would be achievable.

3.1.4.6 System Availability and Reliability Considerations

This configuration is advantageous due to the built-in redundancy that comes as a result of the APU and engine bleed being part of the same flow network. In the event of a single engine or single side bleed system failure, the APU could be used to supply WAI, AFC, or pack flow to the side with the failure while the side with the functioning engine and bleed system is isolated via the isolation valve. The redundancy lends itself well to this architecture and may be required to ensure the reliability of the system is commensurate with the hazard effect of a failure of the AFC system.

It is unlikely that there will be sufficient bleed air available to provide significant AFC performance when the airplane is operating from a single engine bleed and the landing field length of the destination is short enough such that the AFC system is required. In this event, APU air can be used to augment the AFC system on the side with an engine or bleed system failure.

Further studies are required in order to determine the details and likelihood of this scenario. Depending on the expected size and range of the airplane, as few as 1% of missions may be landing field length limited. An airplane dispatching on single engine bleed would not have a problem as long as the landing field length was such that AFC is not required. For dispatch with single engine bleed to a landing field length that does require AFC, then the operator should check to see if icing is present or forecast at the destination airport. If not, then the WAI and EAI system would not be required and the APU could be used to supply the packs and AFC system during landing at the flow rates defined in configuration 3. As stated earlier, the APU has an in-flight restart rate of approximately 99.5%. In this event, it would require a single-bleed failure + a landing field length limited airport + icing conditions + the failure of an APU to cause the airplane to divert to an alternative airport. This is to say that even if the AFC system is unable to provide sufficient performance with a single engine bleed system failed, then there are multiple contingencies that would still allow the airplane to dispatch with that failure and complete the mission if properly planned for.

In the event of a single engine's bleed system failing en route, then the same contingencies would apply and a required diversion to an alternate airport would be unlikely. Further analysis is required to define numeric probabilities of this occurrence but qualitative analysis shows that this configuration should provide good reliability with little to no increased disruption to operators over a baseline airplane with no AFC.

3.1.4.7 System Weight

Of all the AFC configurations that were studied, this one has the smallest weight impact to the baseline airplane. This is due to the minimal amount of additional ducting that is required to supply flow to the actuators in the pylon location of the wing. The system configuration weight is approximately 0.05% OEW.

3.1.4.8 System Limitations and Challenges

The limitation of this configuration is that it is not practical for engine bleed air and APU air to flow in the same duct simultaneously. Therefore, precooled engine bleed air would not be available to the airplane pneumatic systems while the APU is providing flow to the AFC actuators, at least on the side that is being supplied by the APU. If the isolation valve is closed, then one side would still have engine bleed available. Systems that would be impacted by this are the air conditioning packs, WAI system, and NGS. It may be acceptable if the AFC system is only required for a short duration but further requirements analysis and study of the regulations is needed in order to determine if temporary deactivation of these systems is acceptable.

Current airplanes normally provide bleed air to the packs during takeoff unless the airplane is operating at its sizing condition in which the pack flow is temporarily inhibited. Depending on the flow demands of the AFC actuators, the APU may be able to simultaneously provide flow to the A/C packs and the AFC actuators although full performance of the packs combined with significant $C_{L,max}$ improvements from the AFC system may be difficult to achieve simultaneously by way of the APU as a flow source.

If the intended use of this configuration is during the takeoff flight phase, then it is common for the WAI system to be inhibited during this stage on existing airplanes so lack of WAI flow may be acceptable on future airplanes during takeoff to enable sufficient airflow to the AFC actuators. If the intended use of this system is to improve landing performance then it is unlikely that deactivation of the WAI system is acceptable. Wing icing can significantly reduce the $C_{L,max}$ of the airplane which could affect net $C_{L,max}$ improvements that the AFC system may provide in leading edge regions.

3.1.4.9 Configuration Summary

- Engine bleed can supply flow to the AFC actuators during landing while APU air supplies flow during takeoff.

- Largest AFC mass flow available from APU flow source if A/C packs and WAI can be inhibited while AFC system operates.
    - Single engine bleed alone is most likely not a feasible configuration if pack flow and WAI flow cannot be inhibited while AFC system operates. This would need to be supplemented with APU air.
- Significant AFC mass flow is achievable at altitudes below 10,000 feet with all other pneumatic systems operating (AFC actuator pressure ratio of 2 and mass flow rate of 28% max APU flow).
    - At altitudes above 10,000 feet, benefits are still achievable if AC pack flow can be reduced when the AFC system is needed.
    - If other systems can be inhibited, larger AFC benefits may be achievable at pressure ratios of 4 and mass flow rates up to 43% max APU flow.
- Theoretically high levels of AFC system availability/reliability due to flow-source redundancy for this configuration.
- Minimal weight increase to the baseline airplane of 0.05% OEW.
- Effect of increased use of APU must be accounted for in reliability assessments.
- Integration of AFC supply duct and valves at the pylon location appears feasible.
- The major challenge of this configuration is balancing bleed flow uses. Situational challenges may arise in the event of single-engine bleed but thorough mission planning and consideration of potential icing conditions at the destination airport would likely mitigate the frequency of possible landing diversions.
    - Incorporating the APU as a redundant flow source in the event of an engine failure is doable with this configuration to improve overall AFC system reliability and augment the air available to systems that demand pneumatic energy.

3.1.5 Other AFC Configurations Considered

A short synopsis is provided of other AFC energy scenarios considered in current scoping effort. Based on study assumptions and results, these configurations are less likely to provide net integrated AFC benefit to the performance reference aircraft.

3.1.5.1 Electric Compressor, APU, or Engine Bleed to wing leading edge at most outboard Slat

Duct integration in outboard wing leading edge is likely not practical. Only a very narrow duct can be routed through the existing systems and structure. Flow rates required at this AFC location in order to achieve a significant aerodynamic benefit. Pressure losses and sonic fatigue would be high in the transport duct causing noise and leading to duct fatigue.

3.1.5.2 Engine Bleed to aileron or AFC during takeoff

Using engine bleed for the AFC system during takeoff is undesirable due to the effect of bleed air on engine thrust production. Extracting even small amounts of bleed air reduces thrust significantly. Unless the L/D benefits of the AFC system are high enough to offset the thrust reduction that comes as a result, this configuration is not practical. However, an airplane level trade that investigates the compounding benefit of takeoff L/D improvements should be performed to ensure that this is the case. It may be possible (but unlikely) that compounding weight reductions occur with takeoff L/D improvements

3.1.6 Summary and Assessment of AFC Configurations Studied

Table 3 provides a summary of systems weight and challenges of various AFC energy sources scoped in current study. Table 4 provides a qualitative assessment ("expert opinion") of overall systems' impact and practicality of each AFC configuration studied. The "Overall Practicality" score is a qualitatively combined measure of AFC systems' weight, integration challenges, availability, and architecture compatibility aspects for modern aircraft. A score of 5 is the best and 1 is the worst.

Table 3 – Summary of AFC System Weights and Challenges.

Energy Source	Weight Penalty Aileron AFC (% OEW)	Weight Penalty LE Pylon AFC (% OEW)	Other Challenges	Notes
Engine Bleed	N/A	0.038	Negative Thrust Impact (in takeoff) Bleed-air management in landing	Likely not practical for takeoff Can be combined with APU for approach/landing
Auxiliary Power Unit (APU) Load Compressor	0.095-0.121	0.038	APU Reliability Aileron AFC integration	Possible reliability challenges could be mitigated with bleed air backup
ECS cabin-air compressors	0.117-0.142	N/A	Aileron AFC integration	Requires electric ECS as baseline
Dedicated AFC compressors	0.266-0.513	N/A	Aileron AFC integration Reliability of single compressor Spatial integration of additional compressor	Electric compressor not feasible for LE pylon AFC
Battery Powered Compressor	0.313-494	N/A	Aileron AFC integration Reliability of single compressor Spatial integration of additional compressor and batteries	Electric compressor not feasible for LE pylon AFC

Table 4 – Summary of Overall Practicality of AFC Configurations.

Energy Source	Meets AFC Energy Requirement	Availability/reliability	Weight/Penalties (Aileron AFC)	Weight/Penalties (LE Pylon AFC)	Overall Practicality (Aileron AFC)	Overall Practicality (LE Pylon AFC)	Overall Practicality (Slat 1 LE AFC)
Engine Bleed	Scenario dependent	Adequate (Scenario Dependent)	Moderate-High	Minimal	2	3	2
Auxiliary Power Unit (APU) Load Compressor	Adequate	Likely Adequate (Scenario Dependent)	Moderate	Minimal	3	4	2
APU with Engine Bleed backup	Adequate	High	Moderate-High	Minimal	5	5	2
ECS cabin-air compressors	Adequate	High	Moderate (if electric ECS is baseline)	Moderate	3	2	1
Dedicated AFC compressors	Adequate	Likely Adequate (Scenario Dependent)	High	High	2	1	1

3.1.7 AFC System Flow Source Topics for Further Study

3.1.7.1 Opportunities for Weight Reduction

Each configuration conservatively assumed that there are two AFC control valves arranged in parallel to enable system operation in the event that the primary valve fails. This may not be necessary for AFC systems intended for use during takeoff. A system diagnostic test prior to takeoff should assure the flight crew that the valve is operating correctly. An additional valve likely does not significantly improve reliability due to this consideration but it does potentially improves the dispatch ability of the airplane with that failure.

Future studies should determine if insulation of the AFC supply is necessary since that makes up a considerable amount of the total weight. Temperature requirements at the AFC actuators should be established as well as structural temperature requirements for duct leakage to determine if insulation is needed.

Duct sizes were determined with a moderately conservative pressure loss estimates to ensure that the flow at the AFC actuators was suitable. Refined analysis using finite element methods and CFD may result in the ability to downside duct diameters. For configurations distributing flow to the aileron AFC actuators, reducing duct size can have a non-negligible impact on duct and insulation weight.

3.1.7.2 Regulatory Requirements Clarification

For configurations where the AFC air is being supplied by the same flow source that is supplying WAI, NGS, or A/C pack air, the available flow to the AFC actuators depends heavily on whether or not those systems are required for situations where the AFC system is needed. Specifically, it is necessary to know whether or not pack flow can be reduced during the time period at either takeoff or landing when the AFC system is needed. There is some precedent for this considering that pack flow is reduced or shutoff at takeoff conditions where maximum engine takeoff thrust is required.

3.1.7.3 Analysis of System Reliability

System reliability has been addressed to some degree in this document but further analysis is required and is entirely configuration dependent. If the AFC system is inoperable but is required for safe landing, the ability of the airplane to divert to an alternate airport must be considered. Additionally, the necessity for the AFC system must be considered. Is the system used regularly or only on rare occurrences at corner conditions which would otherwise size the airplane? Certification requirements state that a system's failure rate must be commensurate with the hazard effect of that failure.

Combinations of some AFC configurations discussed already as well as flow management of the various users of pneumatic air supply can help increase the reliability of the system. For example, having bleed air as a backup flow source for APU air can provide redundancy with the available flow. But neither of these flow sources can power all of the pneumatic systems simultaneously at all conditions so the complexity of the control logic increases dramatically with an AFC system that is on the same flow circuit as the other systems.

3.1.7.4 Detailed Duct Flow Analysis to Ensure Pressure and Flow Rate are Achieved

For configurations where AFC flow is shared with other pneumatic systems, a detailed analysis must be performed to ensure that the pressure or flow is not being disproportionately used by any one system and then all systems are provided with the flow needed to meet the requirements.

3.1.7.5 Use of Compressed Air Canisters as possible source Supply AFC Flow

This configuration was considered but not studied. Compressed air could potentially be used as a flow source with the canisters being refilled after use via bleed air. The maximum pressure in the canisters would be limited by the pressure available from the air supply system.

4 Integration and Performance Opportunities

This section summarizes results of conceptual performance integration studies performed for the PRA (Performance Reference Aircraft) to estimate the potential airplane-level performance and operational benefits enabled by localized wing AFC applications. Using performance trade factors representative of the PRA configuration, the potential performance opportunities in takeoff and landing for selected wing AFC topics are assessed.

4.1 Integrated benefits of Low-Speed AFC Opportunities on PRA Performance

Referring to Figure 1, AFC net aerodynamic increments are combined with AFC structural and systems weight penalty increments towards integrated aircraft performance opportunities for the Performance Reference configuration. Within the scope of current conceptual study on possible overall benefits of several wing AFC concept using potentially practical AFC energy sources, performance assessments have been done using utilizing preliminary-design performance trade factors applicable to the PRA configuration. These performance trade factors have been derived from detailed performance analyses for the PRA configuration by analysis of impact of variation in aircraft design sizing parameters to meet the low-speed (takeoff and landing) design constraints of the baseline PRA aircraft, while meeting overall mission payload and range requirements. Where possible, the key performance metric used in the current study to assess AFC net opportunity (i.e., including AFC related weight and possible cruise fuel penalties) is fuel burn/seat for the nominal PRA economical mission (range and payload).

This section first provides an introduction to the performance assessment scenarios utilized, and then summarizes conceptual aircraft-level design net performance opportunities that the studied AFC topics could provide to the PRA configuration via AFC high-lift aerodynamic performance enhancement(s).

4.1.1 Key Aerodynamic AFC opportunities to enhance Low-Speed Performance

In Section 2, the possible improvements to key aerodynamic low-speed parameters are summarized for the three local wing AFC concepts studied. Table 5 provides a summary of the key parameters most relevant to takeoff and landing conditions.

Table 5 – Key Aerodynamic Parameters that affect Low-Speed Performance.

AFC Application	**Takeoff**			**Landing**		
	C_L @Alpha	L/D	$C_{L,max}$	C_L @Alpha	L/D	$C_{L,max}$
Aileron	x	**x**	x	**x**	x	**x**
LE OB Slat	x	**x**	x	n/a	n/a	n/a
Nacelle/pylon	x	**x**	x	**in work**	in work	**in work**

4.1.2 Sizing and Nonsizing Performance Assessment Scenarios

For the current study, two performance assessment scenarios were used to scope performance opportunities for the AFC applications evaluated for the PRA project aircraft. Table 6 summarizes the 2 main categories of design assessment performance scenarios for technologies studied here on project aircraft configuration: sizing scenarios and nonsizing scenarios.

In the performance sizing scenarios used in the present study, it is assumed that the aircraft size (wing size, flap area, engine thrust) are determined to meet key requirement constraints for takeoff or landing, while maintaining mission requirements (such as payload and range), and satisfying other design constraints.

Under the scenario that takeoff performance is the critical sizing constraint, takeoff L/D is assumed the key aerodynamic parameter that affects required wing area and engine design thrust used to meet critical takeoff performance at high-elevation airports and at high air temperature, i.e., takeoff climb gradient at engine-out case. Improvements in takeoff L/D due to AFC would results in reduced wing area and reduced takeoff thrust (and, related, engine size), resulting in reduction of OEW and cruise fuel burn.

Under the scenario that landing performance is the critical sizing constraint, $C_{L,max}$ (and related achievable $C_{L,app}$) is assumed the key aerodynamic parameter that would set wing area and/or flap area to meet the target approach speed (V_{app}). Improvements in landing $C_{L,max}$ (and $C_{L,app}$) due to AFC would results in reduced wing area and/or flap area, resulting in reduction of aircraft OEW and cruise fuel burn.

For nonsizing scenarios, the AFC incorporation does not affect the key aircraft sizing elements, but AFC if reliably available can provide operational benefits to airlines. In particular, for takeoffs from Hi Hot airports that have gradient limited takeoff climb profiles, L/D improvements feasible with AFC could allow increase of payload that can be carried by the aircraft from such airports. For takeoff operations from nongradient-limited airports, the operator could reduce engine thrust during takeoff ('derated' engine thrust setting'), reduce takeoff noise and engine operating costs (e.g., reduced engine maintenance, or reduced 'lease-by-hour' fees that dependent on engine thrust settings).

For the nonsizing takeoff scenario considered here, the key merit of improvement is increase in takeoff payload capability. In this study, this was translated into an estimated life-cycle net value revenue opportunity in airline operations.

Table 6 – AFC Performance Scenarios and Key Aircraft Design Benefits.

Category	AFC Aero Opportunity	Key Aircraft Benefits For Take Off	Key Aircraft Benefits For Landing
Sizing Scenarios	**L/D** C_{Lmax}, $C_{L,alpha}$	**Wing area, Engine Thrust,** Take-Off speed schedule	**Wing area, Flap Area,** Engine Thrust
Non-Sizing Scenarios	L/D C_{Lmax}, $C_{L,alpha}$	**Engine Derate, HI Hot payload increase**	Brake wear reduction, tail clearance

4.2 Results - Aileron AFC Aircraft-Level Performance Opportunities

Results are presented for several performance assessment scenarios for takeoff and landing considerations with AFC incorporated on the PRA study configuration.

4.2.1 AFC Opportunities for Aircraft with Takeoff Performance as Sizing Constraint

Application of AFC to drooped symmetric aileron provides L/D opportunities for the takeoff of the improved L/D for sizing high-hot takeoff constraint results in wing area, engine weight and resulting cycled fuel-burn reduction for a typical operational range. The key benefits are size, weight and engine design thrust reduction.

Using trade factor studies for the PRA, the estimated impact of L/D improvement are provided in Figure 26 for assumed AFC system weight addition of 0.125% OEW. The structural weight penalty for changed loading of the wing with AFC on ailerons is included. Under the assumptions in this trade study, a significant net improvement potential for blockfuel/seat-mile exist (on order of 0.4 – 0.6%) if high-hot TKO is the critical sizing constraint for a PRA type aircraft. Aileron deflections above about 16° do not provide further blockfuel/seat benefit. It is noted that limiting the aileron deflection angle with AFC activated will reduce wing structural weight (which impact on blockfuel changes is included in Figure 26), and, hence manufacturing (and purchase) cost of such airplane. Increasing AFC system weight will reduce the blockfuel/seat benefit, but, depending on the magnitude of total AFC weight, AFC can still can have a positive fuel-burn/seat reduction.

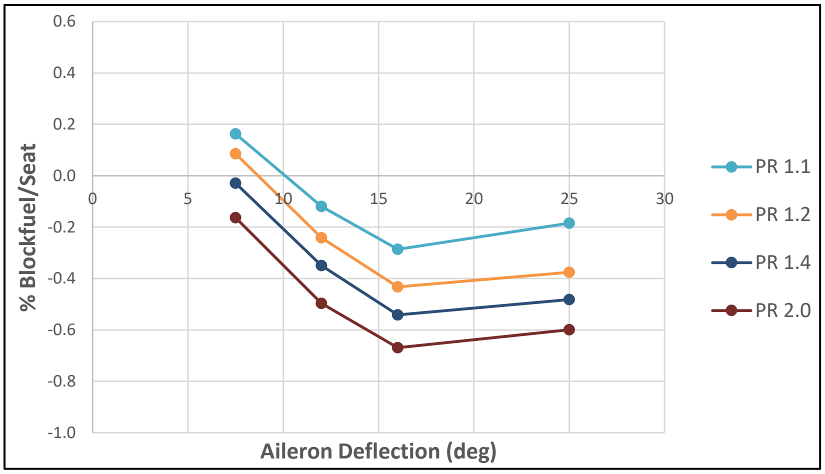

Figure 26 – % Blockfuel/seat change with aileron AFC for aircraft sized for takeoff. Baseline AFC system weight 0.125% OEW (APU door drag included).

These estimated potential fuel-burn improvements enabled by aileron AFC are quite significant, and suggest value in further study with more detailed AFC integration definition and higher fidelity analyses in areas of wing Loads and aeroelastics effects to refine the estimate. If future refined analysis would reduce the assessed AFC benefit somewhat, it is still likely that AFC aileron application can provide a sizeable net performance benefit for scenario where the Takeoff high-hot design case dominates configuration sizing (wing area, engine thrust).

4.2.2 AFC Opportunities for Aircraft with Landing Performance as Sizing Constraint

AFC in landing with aileron deflection can increase $C_{L,max}$ and resulting approach angle of attack. If V_{app} is sizing the wing (and/or flap area), the designer can use AFC in lieu of growing the wing (or flap area, or a combination).

Figures 27 and 28 provide a range of possible benefits for the sizing case where wing area is scaled using the $C_{L,app}$ benefit with AFC to achieve target V_{app}. A benefit of 0.1 - 0.25% reduction in fuelburn/seat is estimated to be possible for assumed AFC system weight penalty for aileron deflections of 12° - 16°. The increments are smaller in the landing sizing scenario than for the takeoff L/D scenario. If larger aileron deflections are feasible, the landing scenario predicts increased AFC increment, up to 0.35% (Figure 27).

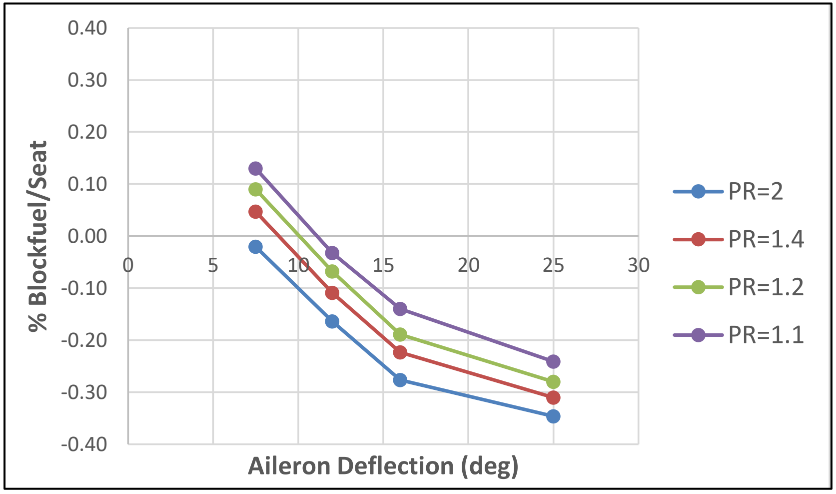

Figure 27 – % Blockfuel/seat change with aileron AFC (landing wing size trade to maintain V_{app}). (APU door drag included). AFC system weight 0.125% OEW.

An alternate approach to increasing the overall wing area to reduce approach speed is to enlarge the relative flap area. Generally, the weight implication of this approach is smaller than resizing the entire wing. As a result, the relative fuel-burn benefit of aileron AFC (in view of associated AFC systems and wing structural penalties) can be expected to be smaller than for the wing-sizing landing scenario. Figure 28 indicates that even with the nominal AFC aileron system weight penalty of 0.125% OEW, there is no net benefit that AFC can provide for this sizing scenario.

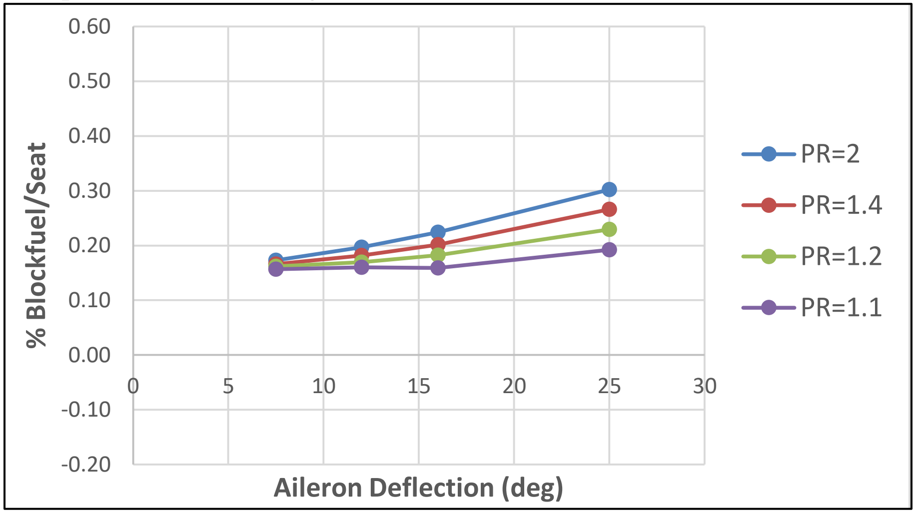

Figure 28 – % Blockfuel/seat change with aileron AFC (landing flap area size trade to maintain V_{app}). (APU door drag included). AFC system weight 0.125% OEW.

4.2.3 AFC Opportunities for Takeoff Performance for Existing Configuration (Nonsizing Scenario)

In this scenario, the takeoff performance is not the critical sizing constraint. The change in takeoff Aerodynamic performance (L/D) would not change the design size of the wing, high-lift system and/or engine thrust setting of the performance reference aircraft, however, AFC could favorable impact the takeoff performance on actual missions departing from gradient-limited airports. A suitable AFC system would allow the airline to carry a larger passenger load than in the absence of the AFC L/D enhancement. In addition, the engine thrust at all nongradient limited airports could be somewhat reduced, allowing the airlines to reduce maintenance cost or by-the-hour engine lease costs. The benefit assessment is done using an approximate airline lifecycle value benefit.

Table 7 presents a summary of takeoff performance opportunities for aileron droop at PR1.4 for gradient-limited takeoff (relative to baseline aileron droop without AFC). L/D improvement with AFC could provide a significant % increase in payload weight capability for gradient limited airports, and, with the AFC system operated, could provide relevant reduction in engine takeoff thrust setting for nongradient limited airports. Table 7 also indicates small adverse impact of adding AFC structural and systems' weight increments to the aircraft, with a small increase in block fuel needed to complete the baseline mission range. For shorter-range aircraft, the operational impact of AFC related increased fuel burn is relatively minor (but reduces the operational value of AFC somewhat).

Table 7 – Aileron AFC impact for nonsizing takeoff scenario.

Aileron droop (deg)	Net payload increase (gradient limited airports)	Block fuel change (economical mission)	Engine takeoff thrust derate (nongradient limited airports)
7.5	1.9%	+ 0.12%	0.8%
12	5.6%	+ 0.18%	2.0%
16	8.0%	+ 0.23%	2.9%
25	8.3%	+ 0.32%	3.1%

The operational net value to airline operators due to the impact of payload benefit (while accounting for the small block-fuel change) with AFC was assessed using a Life-Cycle benefit analysis. In the current scoping study it was assumed that 25% of all takeoffs for an airline are gradient limited and AFC would allow payload increases as indicated in Table 7. The remaining 75% of takeoffs for these same airline are nongradient limited, and are assumed to benefit from engine takeoff thrust derating. Penalties for some increased maintenance (APU systems) is included. Figure 29 indicates that with these assumptions a significant increase in net life-cycle airline value can be expected per airplane (i.e., potentially on the order of several $M over the operational life time). It is noted that the increase in aircraft weight due to structural and systems changes, as well as the cost for added AFC systems, will increase the manufacturing cost of an aircraft equipped with an AFC system.

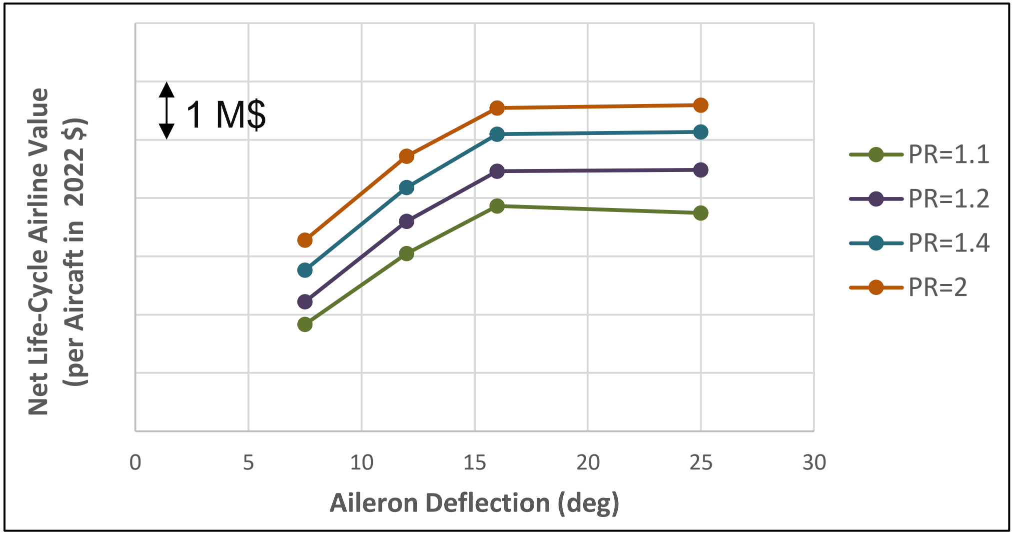

Figure 29 – Estimated life-cycle operator value for aileron AFC in operational use for assumed fraction of gradient limited takeoffs.

4.3 Results – LE Wing AFC Aircraft-Level Performance Opportunities

Results are presented for available performance assessments for takeoff considerations with AFC incorporated on the study configuration to the wing leading edge AFC concepts studied.

4.3.1 Leading Edge Wing at Outboard Slat AFC – Takeoff

Figure 30 indicates possible net fuel-burn/seat improvements with AFC integrated in the leading edge near the outboard slat. For the baseline AFC system weight, a small improvement up to 0.1% in fuel-burn per seat is possible – albeit at very high PR (probably not practical at the outboard wing in view of duct losses). Increasing AFC system weight to heavier energy sources will quickly erode any AFC opportunity aimed at the takeoff L/D improvement.

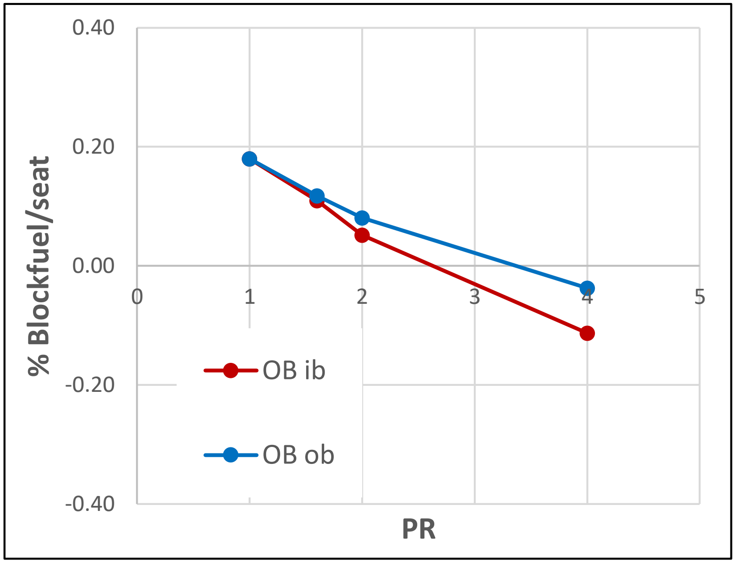

Figure 30 – % Blockfuel/seat change with outboard slat AFC for aircraft sized for takeoff (baseline AFC system weight 0.125% OEW); APU door drag included).

4.3.2 Nacelle/Pylon/Wing Region

4.3.2.1 Nacelle/Pylon/Wing Region – Takeoff

Takeoff sizing scenario for nacelle/pylon/wing application was assessed for most practical AFC layout considered in Section 3 (APU/bleed combined). The performance improvement with AFC provides a takeoff L/D benefit that translated into a blockfuel/seat sizing increment up to 0.2% for higher PRs (see Figure 31).

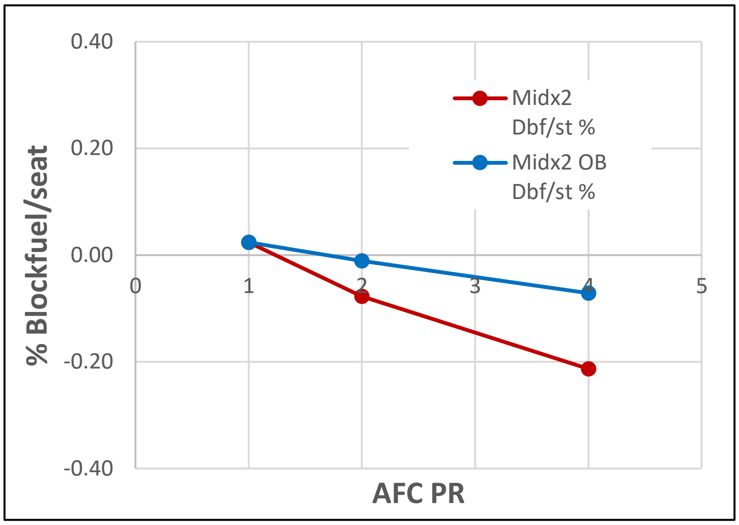

Figure 31 – % Blockfuel/seat change with Nacelle/Pylon/Wing AFC for aircraft sized for takeoff (APU/Bleed AFC System Weight).

4.3.2.2 Nacelle/Pylon/Wing Region – Landing

Preliminary CFD results on the CRA configuration for the landing configuration with Nacelle/Pylon/Wing Region AFC actuation studied suggest a significant increase in $C_{L,max}$. Results are for initial nonoptimized AFC actuator position in this region with complex flows. It is reasonable to expect that predicted improvement for the CRA translate to significant $C_{L,max}$ (and $C_{L,app}$) opportunities for the PRA configuration. Based on the landing performance potential estimated for AFC on the aileron (see Sections 4.2.1 and 4.2.2), a material fuel-burn opportunity with nacelle/pylon/wing AFC can be realized for the PRA.

Future study is needed using detailed CFD explorations to properly quantify (sizing and nonsizing) landing performance opportunities using nacelle/pylon/wing AFC concepts on the PRA.

4.4 Summary Assessed AFC Aircraft Net Performance Benefits

The localized wing AFC applications topics studied here at a conceptual integration level are found to provide relevant net performance opportunities for the PRA configuration – under the assumptions and analyses of current study. The integration scoping study focused on characterization of concepts from the CFD study. Of the three localized concepts, the drooped aileron application provides the most significant takeoff net performance benefit opportunities. AFC in the nacelle/pylon/wing region may provide most benefit for the landing configuration. The wing leading edge application near the outboard slat was explored in CFD only for the takeoff configuration on the CRA; it is possible that relevant flow-control benefits are available in the landing setting. Integration of AFC ducting and actuation system in the outboard-wing in front of the front spar will be most challenging on small aircraft. Future high-aspect-ratio wings with small chords have very limited volume available for routing AFC ducts or integrate small electrical compressors.

Additional study of current (and possible other) localized wing AFC applications are needed to enhance understanding of integrated net performance opportunities. Recommendations on future studies are provided in Section 5.

4.5 Comparison to Previous AFC Integration Studies

Conceptual integration trade results for localized wing AFC applications studied in current study can be compared to previous AFC integration study on the vertical fin/rudder of a medium-sized passenger aircraft [9]. The main opportunity for vertical fin/rudder AFC application is the potential to reduce the size of the vertical fin for a family of aircraft and hence, allowing less cruise drag and reduced OEW, while maintaining rudder/fin control requirements.

Assuming the same performance sizing trade factors as used in current wing AFC study for the PRA configuration, and assuming the cruise drag, SFC and weight impacts due to AFC on the vertical fin in Ref 9 (using ‘most likely’ estimates for the sweeping-jet AFC system in Table 4 therein) apply to the PRA, the benefit for AFC applied to the PRA vertical fin would be an approximate 0.2 - 0.25% reduction in blockfuel/seat.

The localized wing AFC topics studied in current study suggest potentially somewhat larger integrated airplane benefits than the vertical fin/rudder AFC application study found. It is noted that current scoping study of wing AFC topics is at a more conceptual level (and with smaller work statement) than the detailed rudder AFC integration study reported in Ref. 9.

5 Conclusions and Next Steps

5.1 Conclusions

A conceptual integration study was performed on application aspects of potential localized wing AFC concepts on a relevant single-aisle performance reference aircraft with main objectives to determine AFC energy integration and potential net performance gains. The conceptual study focused on the use of AFC over deeper-deflected ailerons, and wing leading edge regions, to enhance low-speed takeoff and landing performance. Most effort in current study was directed at aileron AFC opportunities.

The study translated CFD predicted AFC high-lift aerodynamic increments for the AFC concepts on a similar aircraft configuration to net aerodynamic increment for the performance reference aircraft using preliminary-design analysis methods. Structural weight penalties were identified for the AFC concepts.

A significant portion of the study focused on conceptual assessment of existing or new energy sources to provide AFC pneumatic flow (mass flow and pressure) to AFC actuators. Integration of ducting and control system in the wing trailing edge and leading edge was scoped to assess feasibility of spatial integration as well as to estimate additional AFC systems weight. Focus was on reviewing whether existing power sources already onboard modern aircraft (such as engine bleed, APU load compressor, or ECS compressors) could possibly provide viable net performance benefits with localized wing AFC to enhance high-lift aerodynamics.

The next sections provide specific conclusions concerning integration and opportunities of local-wing AFC concepts studied, as well as specific systems' integration topics.

5.1.1 Aileron AFC Applications

The aerodynamics and flow-control physics of AFC application to deflected ailerons are reasonably well understood. AFC applied to deflected ailerons in takeoff could provide 2 – 5% potential net aerodynamic performance gain in L/D (including assessed trim, aero elastic and structural effects).

The required energy (pneumatic mass flow and PRs 1.4 – 2) for localized AFC could probably be supplied by an existing onboard system (APU load compressor and/or bleed air) with reasonable system weight penalty, whereas novel supply architecture (compressors) – possibly powered by high-voltage/high-density batteries - may be suitable for certain AFC applications.

The APU Load compressor likely has capacity to provide energy for the local AFC concepts studied on the reference aircraft. Availability of the APU/bleed-air energy source at all takeoff and/or landing flight conditions will need further detailed FHA studies. (FHA studies were beyond scope of current initial assessment study.)

Using the estimated integration penalties, an aileron AFC application could provide up to 0.5% blockfuel/seat performance improvement for large aileron deflections if AFC is used to mitigate the high-hot Takeoff sizing constraint. Increasing aileron deflection with AFC over 16° in Takeoff does not provide additional integrated performance benefit. Recognizing uncertainty in AFC related weight increments estimated in current conceptual study, it is possible that a practically integrated aileron AFC at realistic PR and mass flow could provide ~ 0.2 – 0.4% net blockfuel/seat opportunity if high-lift constraints are sizing the configuration.

Aileron AFC could potentially provide ~0.2–0.3% blockfuel/seat opportunity if AFC is used to mitigate V_{app} constraint (i.e., landing sizing scenario).

For nonsizing performance scenarios, aileron AFC application could allow improved operational Takeoff performance for given engine thrust from gradient-limited airports and allow engine derating in other takeoffs. When leveraging existing air supply option (e.g., an operational APU during takeoff), the weight added for aileron AFC application is substantially less than predicted gains in additional takeoff performance capability payload. This option provided by AFC could provide significant life-cycle value benefit to airline operators of an aircraft designed with AFC for high-lift operations.

5.1.2 Wing Leading Edge AFC Applications

Two AFC applications on the wing leading edge were studied. One AFC application topic is on the upper-surface outboard wing leading edge near the slat deployed in the takeoff setting (representative of a ‘sealed slat’). Available CFD exploration results suggest relevant L/D increments and a modest increase in C_L at alpha at higher PRs, in takeoff for this AFC integration. Further understanding of aerodynamic and flow physics effects underlying the predicted AFC increments is recommended.

In takeoff, AFC application near outboard slat could provide 1.5 – 2.0% potential net performance gain in L/D for available mass flow at PRs 2 – 4 from existing onboard systems (APU and/or bleed air). The assessed systems weight for the AFC system to duct compressed air to the outboard slat region results in, at best, a small ~0.1% fuelburn/seat performance benefit for the sizing takeoff scenario.

Another wing leading edge concept studied here is applying AFC flow to the nacelle/pylon/wing junction. CFD available for takeoff conditions suggest relevant L/D increments and significant increases in C_L at alpha and $C_{L,max}$, particular at higher PRs, AFC applied to nacelle/pylon/wing region could provide a ~0.1 – 0.2% potential net blockfuel/seat performance gain (takeoff sizing scenario) due to L/D improvement during takeoff using bleed-air/APU energy.

Preliminary CFD results for nacelle/pylon/wing junction AFC in the landing configuration suggest relevant increase in $C_{L,max}$. It is reasonable to expect that this will translate to a relevant $C_{L,max}$ opportunity for the PRA configuration in landing. Based on landing net performance potentials estimated for AFC on aileron (see earlier section), a significant opportunity with nacelle/pylon/wing AFC is possible. This is a topic for future study.

5.1.3 AFC Systems Integration Assessment Conclusions

The required flow for AFC (mass flow and PR) can generally be supplied by already existing onboard systems (but extra ducting and systems hardware is required). In particular, the APU load compressor operated during takeoff (and landing) can provide AFC energy requirements for applications scoped in current study. From this scoping study, it appears likely that an operational APU can provide AFC energy with adequate availability for the critical engine-out takeoff case. Detailed Functional-Hazard Assessment (FHA) studies are needed to confirm requirements for APU availability/reliability in all takeoff and also possible landing cases were AFC enhances aerodynamic performance.

Bleed air can be used as the primary AFC flow source during landing with proper mission planning and pneumatic system flow management (WAI, EAI, A/C Packs). Bleed air can be used as backup flow source when thrust detriment is too high to use as primary flow source during takeoff.

The study defined conceptual spatial integration of AFC actuators, ducting, and pneumatic control for the three wing AFC application topics considered. Integration of AFC ducts in the wing trailing edge appears conceptually feasible, but detailed installation of AFC actuators near the aileron actuation system is expected to be challenging on smaller aircraft. Spatial integration of ducting and AFC actuators in outboard wing leading edge is very challenging on smaller airplanes. On the other hand, proximity of existing pneumatic ducting in nacelle/pylon/wing junction region would greatly reduce added systems weight for AFC application in this region. Relative to the outboard wing integration challenges, the nacelle/pylon/wing region appears to have spatial opportunities for AFC integration.

5.1.4 Overall Conclusions from Current Study

Current conceptual aileron AFC application studies suggest significant performance opportunity for aircraft design for takeoff sizing scenario. If not sizing, aileron AFC could provide relevant life-cycle benefit to operators (high-hot takeoff payload increase or increased engine derating opportunities). Aileron AFC could provide also net performance opportunity for aircraft design under a landing sizing scenario.

AFC on leading edge (behind deployed slat) on outboard wing could provide a relatively small sizing benefit in takeoff. Additional local flow control opportunities may exist in outboard wing/wing-tip region, warranting further CFD and integration exploration. However, ducting of AFC energy flow to the wing outboard leading edge is very challenging for smaller aircraft.

AFC application in the nacelle/pylon/wing region may provide useful flow control opportunities. Available CFD on the CRA indicates significant potential for aerodynamic enhancements. Further understanding of the flow-control opportunities in this region near $C_{L,max}$ on optimization of high-lift configurations is recommended using CFD at both landing and takeoff conditions.

The current study showed that the APU could be an attractive existing energy source for local wing AFC with relatively moderate systems' weight implications. Availability of APU energy appears likely adequate for the high-lift applications studied. Follow-on studies are needed with detailed FHA and maintenance/cost considerations for APU operations for AFC in takeoffs and landings.

5.2 Next Steps

The current study was aimed at conceptually scoping potential net performance benefits and integration challenges for local wing AFC concepts. Performance benefit studies were based on AFC increment estimates using conceptual-design methods such as performance trade factors for the reference aircraft.

A set of recommended next steps are suggested to support higher fidelity studies to refine estimation of AFC increments for one or more wing application studied.

1. Conduct additional detailed CFD simulations on wing local AFC.
2. Conduct wind-tunnel testing at adequate scale on suitable model to validate CFD aerodynamic increments improvements (and requirements).
3. Progress detailed design integration of AFC actuators to provide efficient flow control at aileron and leading edge locations.
4. Progress detailed mechanical design of AFC power routings in wing leading and trailing edge.
5. Use high-fidelity modeling methods to verify loads, structural/aeroelastics and weight increments associated with AFC generated changes in aerodynamic loading during takeoff and landing. Consider possible synergisms of AFC for wing load alleviation.
6. Conduct follow-on studies of AFC energy systems with detailed functional-hazard assessment.
7. Conduct design trade studies on AFC impact on high-lift sizing of aircraft family – $C_{L,max}$ and attitude constraints. Include community-noise assessment of AFC operations in takeoff and landing.
8. Conduct airline operations benefit simulations to further quantify economical value of AFC applications (e.g., engine derating). Include maintenance/cost considerations for regular APU operation in flight for AFC.
9. Consider possible other wing AFC application topics / integration opportunities not considered in current study.
10. Scope wing AFC technology maturation plan beyond design studies to understand ground and flight test (including flight demonstrators) requirements to evaluate integrated full-scale hardware at operational conditions.

References

1. McLean, J. D., Crouch, J. D., Stoner, R. C., Sakurai, S., Seidel, G. E., Feifel, W. M., & Rush, H. M., "Study of the Application of Separation Control by Unsteady Excitation to Civil Transport Aircraft," *NASA Technical Report*, NASA/CR-1999-209338, June 1999.
2. Hartwich, M.P., Camacho, P., El-Gohary, K., Gonzales, A.B., Lawson, E.L. and Shmilovich, A., "System-Level Trade Studies for Transonic Transports with Active Flow Control (AFC) Enhanced High-Lift Systems," AIAA 2017-0321, DOI: 10.2514/6.2017-0321
3. Shmilovich, A., Yadlin, Y., Dickey, D.E., Hartwich, M.P., & Khodadoust, A., "Development of an Active Flow Control Technique for an Airplane High-Lift Configuration," *AIAA SciTech Forum*, Grapevine, TX, Jan 9-13, DOI: 10.2514/6.2017-0322
4. Whalen, E.A, Shmilovich, A., Spoor, M., Tran, J., Vijgen, P., Lin, J.C., & Andino, M., "Flight Test of an Active Flow Control Enhanced Vertical Tail", *AIAA Journal*, Vol. 56, No. 9, 2018, DOI: 10.2514/1.J056959
5. Andino, M.Y., Lin, J.C., Seele, R., Graff, E.C., Gharib, M., Whalen, E.A., & Wygnanski, I.J., "Active Flow Control on Vertical Tail Models", *AIAA Journal*, Vol. 57, No. 8, 2019, DOI: 10.2514/1.J057876
6. Lin, J.C., Pack Melton, L.G., Hannon, J., Andino, M.Y., Koklu, M., Paschal, K.C., & Vatsa, V.N., "Wind Tunnel Testing of Active Flow Control on the High Lift Common Research Model", *AIAA AVIATION Forum*, Dallas, TX, June 17-21, 2019, DOI: 10.2514/6.2019-3723
7. Lin, J.C., Pack Melton, L.G., Hannon, J., Andino, M.Y., Koklu, M., Paschal, K.C., & Vatsa, V.N., "Wind Tunnel Testing of High Efficiency Low Power (HELP) Actuation for Active Flow Control", *AIAA SciTech Forum*, Orlando, FL, Jan 6-10, 2020, DOI: 10.2514/6.2020-0783
8. Shmilovich, A., Vijgen, P., & Woszidlo, R., "Low-Speed Performance Enhancement using Localized Active Flow Control – Localized Active Flow Control Simulations on a Reference Aircraft", *NASA Technical Reports Server*, April, 2022, document ID: 20220006731
9. Mooney, H.P., Brandt, J.B., Lacy, D. S, & Whalen, E. A., "AFC-Enabled Vertical Tail System Integration Study," *NASA Technical Report*, NASA/CR–2014-218168, March 2014.