Conceptual Integration Studies of Localized Active Flow Control on the Wing of a Commercial Aircraft

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A study of conceptual integration and performance of localized active flow control technology onto wings of short-to-medium-range project passenger airplanes is summarized. Using predicted aerodynamic performance improvement opportunities on a computational fluid dynamics reference aircraft, this paper presents the estimated performance opportunities for conceptual implementation of studied wing localized active flow control technology for low-speed (takeoff and landing) application on a Project Research Aircraft configuration. Using conceptual active flow control systems and structural integration weight penalties for studied concepts, potential relevant net performance benefits can be obtained with reliable active flow control in takeoff and landing. The conceptual integration study identifies potential localized wing active flow control application opportunities for high-lift conditions using energy sources available on modern aircraft. Material benefits are estimated for takeoff and landing configurations for selected localized wing active flow control applications. The study concluded that substantial low-speed Maximum Lift and Lift/Drag related performance improvements may be possible with localized wing high-lift active flow control systems powered by auxiliary power unit, engine bleed, or electrical compressors - with due consideration of integration and weight impacts as well as availability requirements of such systems.

I. Nomenclature

Parameters

A_{ref}	Wing reference area
α	Angle of attack
C_D	Airplane drag coefficient
C_L	Airplane lift coefficient
$C_{L,max}$	Maximum lift coefficient
C_q	mass flow coefficient, $m_j/(\rho_\infty u_\infty A_{ref})$
L/D	Lift-to-drag ratio

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$\Delta(L/D)$	Percentage delta in lift-to-drag ratio, $100\cdot[(L/D)_{AFC}-(L/D)_{baseline}]/(L/D)_{baseline}$
M	Mach number
$\dot{m}$	mass flow, lbs/sec
$P_{0\infty}$	Freestream total pressure
PR	Total pressure ratio, $P_{0in}/P_{0\infty}$
u_∞	Freestream velocity
V	Aircraft speed
x,y,z	streamwise, spanwise and vertical coordinates, resp.

Subscripts

App	approach
∞	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
HLCAT	High Lift Configuration Analysis Tool
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

II. 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, tunnel and flight tests over the last two decades [1–9]. AFC at subsonic low-speed conditions in the takeoff and landing phases 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 flows at high pressures, the prospective use of localized AFC applied to smaller regions on existing wing high-lift trailing and leading edge (LE) 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. Available CFD simulations point to relatively modest AFC energy (mass flow and pressure ratios) requirements to provide possible relevant aerodynamic benefits [10–12].

Localized wing AFC application 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, the low-speed lift-to-drag ratio (L/D) is a major determinant of performance (in particular on twin-engine aircraft) and an increase in L/D could allow for potentially larger airplane payload, reduced runway length, and/or longer range, which can translate to potentially substantial aircraft 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. An increase in lift at a given angle of attack may alleviate attitude constraints at rotation during takeoff, potentially facilitating integration of airplane-family members with longer fuselage lengths. Landing performance is largely driven by $C_{L,max}$ of wing with flaps in landing detent, and increased $C_{L,max}$ allows reduced approach speed V_{app} for given wing size.

Promising approaches identified in this study target different areas of the wing for possible localized AFC implementation. In one application AFC is used to improve aerodynamic performance of ailerons that 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 AFC at aileron hinge line and selected wing LE applications were explored in CFD. Available CFD results suggest potentially relevant improvement opportunities in key aerodynamic parameters that can affect low-speed high-lift performance and integration [10–12]. The overarching objective of the current study was to scope potential performance and integration opportunities and challenges for several localized AFC wing applications. AFC systems integration and resulting performance assessment for aileron and wing LE AFC applications are studied at a conceptual level.

In this paper, results of conceptual integration studies using several AFC layouts and energy sources are considered for the aileron and a wing LE application. Systems assessment is done both for energy sources already available 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 obtained from Refs. [10–12] are translated to the Performance Reference Airplane (PRA) configuration, including trim, aeroelastic, and structural loading effects.

For the localized wing AFC applications studied, 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.

III. Integration Study Approach

This section provides information on the project aircraft configuration used as the Performance Reference Aircraft (PRA) in current conceptual AFC integration assessments. The analysis approach used to scope potential AFC increments is outlined, followed by the description of the Performance Reference Aircraft.

A. Analysis Process

The present integration study leverages the aerodynamic results from detailed CFD simulations of local AFC applications to the CFD reference aircraft (CRA). The predicted aerodynamic enhancements of local AFC on selected wing regions in takeoff and landing flight conditions are reported by Shmilovich et al. [10–12]. The aerodynamic assessment with AFC is then utilized in aircraft performance analysis tools for a project configuration that is representative of short/medium-range, twin-engine transonic airplane project studies. The geometry definition, which includes fuselage, wing, Krueger flaps, slats, single-element flaps, nacelle/chine, aileron, etc., was adequate for the CFD and integration/systems analysis.

Figure 1 provides a schematic outline of inputs and increments used to assess performance opportunities on the PRA in the current study. 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).

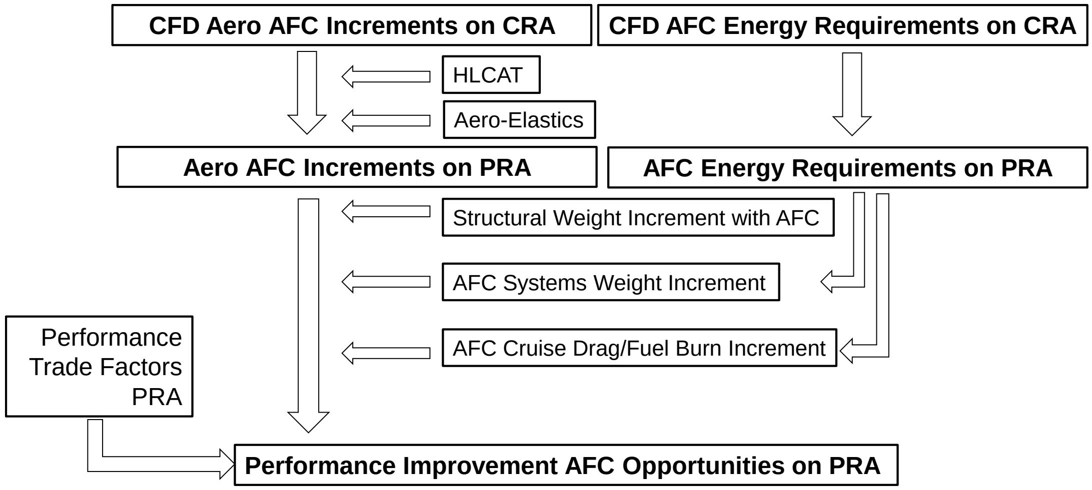

Fig. 1 Analysis steps for conceptual AFC study (CRA=CFD Reference Aircraft; PRA=Performance Reference Aircraft).

B. Performance Reference Aircraft

This section introduces the Performance Reference Aircraft (PRA) used in the 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 of product-development project studies for possible future short-to-medium range single-aisle passenger aircraft. Inboard and outboard flaps have Fowler motion, and the aileron is symmetrically drooped in takeoff. The illustration in Fig. 3 does not show wing spoilers or nacelle/nacelle-pylon located between LE devices 4 and 5. Consistent with the computational CRA configuration used (Fig. 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 detent).

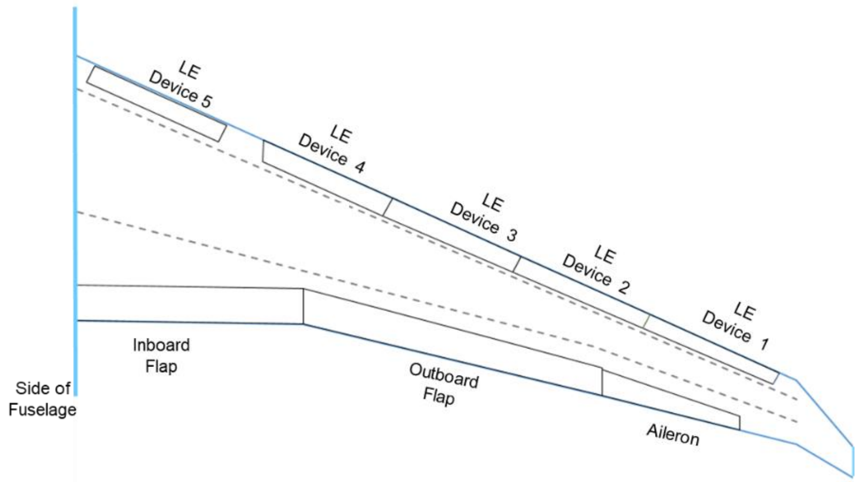

Fig. 2 Schematic wing planform and high-lift elements on Performance Reference Aircraft (PRA) configuration.

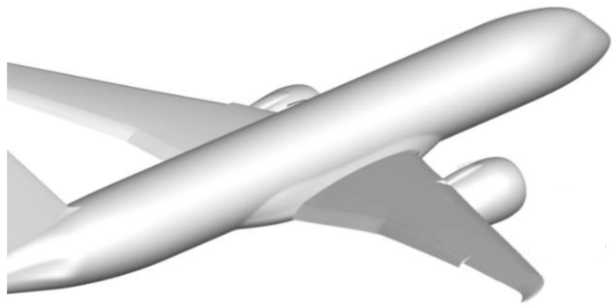

Fig. 3 CFD Reference Aircraft (CRA) configuration (Shmilovich et al. [10–12]).

The wing planform shape of the Performance Reference Aircraft is aerodynamically very similar to the Computational Reference Aircraft Configuration (CRA) used in the numerical studies by Shmilovich et al. [10–12]. 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) used in this study for the CRA configuration is similar (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. The increments are scaled to the PRA configuration to account for (relatively) minor geometry differences via the HLCAT analysis process.

IV. Results

This section first 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. The effect of increased spanwise loading associated with flow control on wing structural weight is estimated using conceptual-design trades to account for changes in wing-root-bending-moment on the PRA wing (under baseline load-alleviation assumptions) with AFC activated. Next, multiple variations of AFC actuators and flow sources were studied to determine the aerodynamic benefit and integration impact of each configuration. This section describes the most feasible and beneficial combinations of AFC actuator placement and flow sources. AFC actuators in the wing trailing edge at the ailerons and at the wing leading edge at the engine pylon location are discussed. The APU load compressor, electrical compressors, and engine bleed are also discussed as possible AFC flow supply together with integration, weight, and performance considerations of each. Further details on the assessments can be found in Ref. 13. Finally, results of conceptual performance integration studies are performed for the PRA (Performance Reference Aircraft) toward estimated airplane-level performance and operational benefits. Using performance trade factors representative of the PRA configuration, the potential performance opportunities in takeoff and landing for selected wing AFC topics are assessed.

A. AFC Aerodynamic Increments

This section provides a summary of key aerodynamic increments in takeoff and landing configurations due to AFC on the Performance Reference Aircraft for selected localized wing AFC application concepts, 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. Increments for AFC application to the outboard slat region are summarized in Refs. 11 and 12.

1. Aileron – Takeoff

Takeoff aerodynamic increments are summarized for the AFC application to drooped ailerons. The CFD results for the aileron AFC application and settings on the CRA configuration were scaled and trimmed to account for the geometry differences between PRA and CRA using the Boeing HLCAT (High Lift Configuration Analysis Tool) performance polar buildup method (Fig. 1). 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, Fig. 4 summarizes the HLCAT derived changes in takeoff L/D for the PRA for various aileron droops and AFC applied at a pressure ratio (PR) of 2.

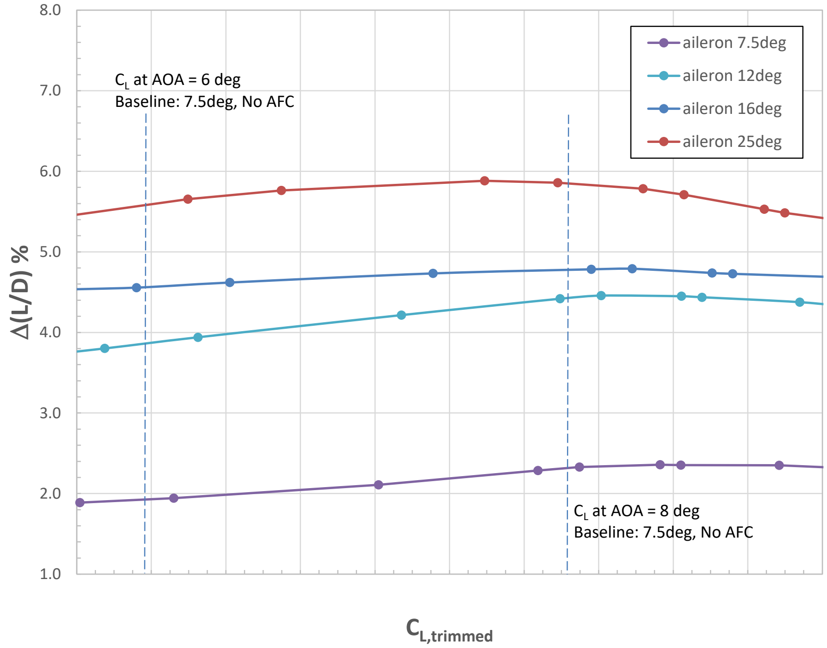

Fig. 4 Aileron AFC: HLCAT takeoff L/D increments for PRA (PR=2). Deltas relative to baseline takeoff aileron deflection (7.5°).

The CFD results for the CRA for various aileron deflections and AFC power settings were obtained for a rigid geometry (i.e., using nominal low-speed wing-twist and flap shapes/settings appropriate for takeoff). Aeroelastic effects of changes in wing twist and camber due to modified wing spanwise loading with deeper aileron deflections and AFC application were estimated using approximate aeroelastic corrections and are included in the resulting net aerodynamic AFC increments. The resulting adjusted net AFC aileron L/D increments used in subsequent performance-impact analysis on the PRA configuration are summarized in Fig. 5. Compared to the CFD increments for AFC on the CRA aileron [10,12], the combined impact of polar buildup from CRA to PRA, trim and thrust effects, as well as aeroelastic corrections, results in a reduction of the net achievable 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 AFC mass flows and PRs considered.

Reflecting the CFD increments on the CRA used as a starting point, there is no additional aerodynamic benefit to consider AFC aileron deflections beyond about 16°. Limiting aileron AFC droop to below larger values will minimize potential adverse impacts on stability and control (roll authority), aileron actuator sizing/integration and aileron structural weight.

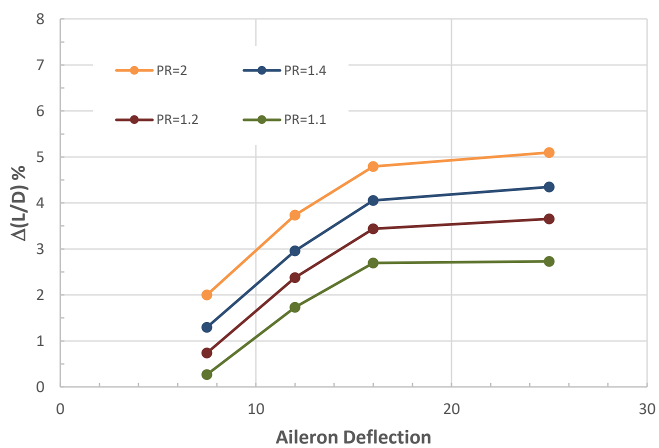

Fig. 5 Aileron AFC: Takeoff L/D increments for PRA including aeroelastic effects. Deltas relative to baseline takeoff aileron deflection (7.5°).

The AFC mass flow requirements on the CRA configuration via CFD [10,12] at analyzed freestream conditions were adjusted to apply to operating conditions and geometry (size/areas of the AFC actuator exit) 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. The aileron AFC actuator at the aileron hinge line is assumed to result in a small aft-step in the cruise wing shape. The resulting local change in local flow field results in a (small) fuel-burn penalty in cruise due to additional excrescence drag. This increment is included in the AFC performance assessment discussed in later sections. Related, if AFC energy is supplied by the APU during high-lift conditions operations, operation of the APU requires the APU inlet door to be open during takeoff and/or landing – with concomitant drag increase. This drag increase during the takeoff/landing phase is included as a reduction in achievable AFC L/D increment used as input to the performance assessments.

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

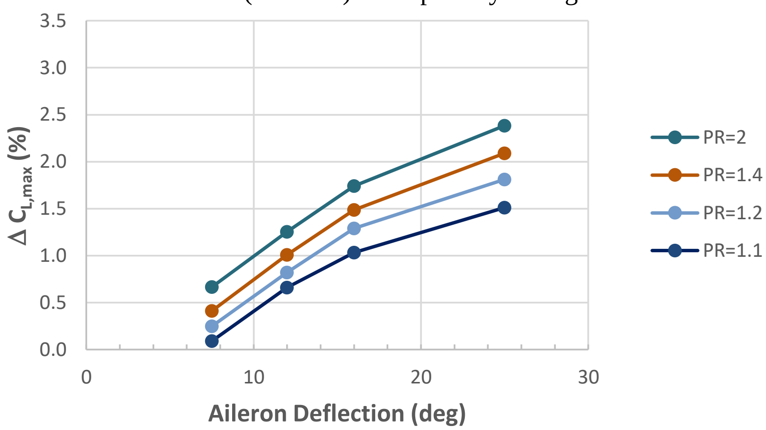

Fig. 6 Aileron AFC: Takeoff $C_{L,max}$ increments for PRA including aeroelastic effects. Deltas relative to baseline takeoff aileron deflection (7.5°).

2. Aileron – Landing

The landing results presented next for the PRA configuration pertain to a landing flap detent (with leading edge slat elements positioned in gapped landing position and the Fowler flaps deployed at landing deflection). The PRA configuration in the current study has no aileron droop in the baseline landing configuration. The CFD simulations performed on the CRA also do not have aileron droop in the landing detent [10,12]. Following the approach and methods used to estimate the takeoff AFC increments, CFD increments on the CRA with AFC in the landing configuration were translated to the PRA configuration with aeroelastic effects 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 with deeper effective aileron deflections could translate in a relevant reduction in V_{app} of about 1–1.5%.

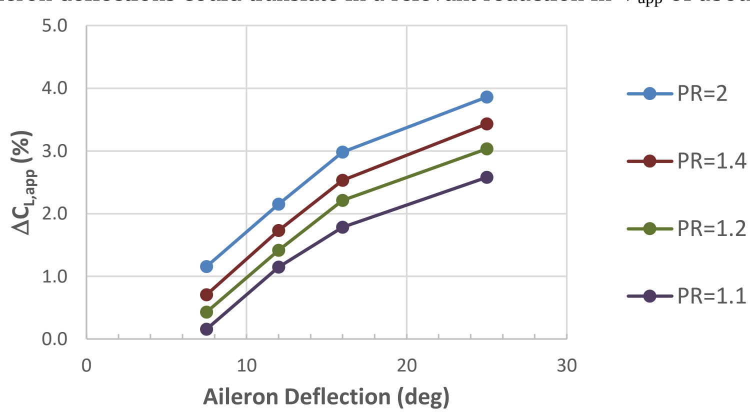

Fig. 7 Aileron AFC: Landing $C_{L,app}$ increments for PRA, including aeroelastic effects. Deltas relative to baseline landing aileron deflection (0°).

3. Wing Leading Edge - Takeoff

Using CFD predicted AFC increments for the CRA for the takeoff configuration [11,12], the build-up process was used to trim and scale takeoff increments to the PRA configuration for an AFC actuation layout applied to the wing leading edge in the nacelle/pylon/wing junction in takeoff. Increments for AFC application to the outboard slat region (Ref. 11) are summarized in Ref. 12. Figure 8 summarizes estimated ΔL/D% increments for various PR settings from spanwise AFC actuation regions embedded in the fixed leading edge adjacent to the nacelle pylon after translation to the PRA. See Refs. 11 and 12 for layout and nomenclature for the AFC actuators in this wing region. The L/D increment due to AFC for the takeoff setting varies from ~0.3% at PR=1.6 to 0.5 – 1% at PRs of 2 – 3.

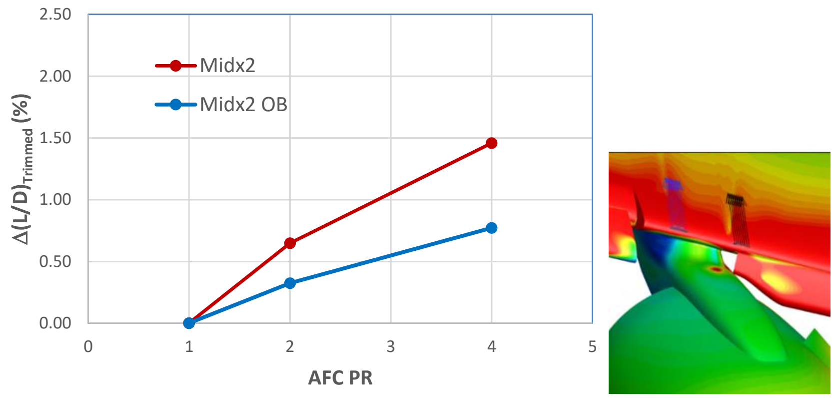

Fig. 8 AFC at Nacelle/Pylon/Wing junction: Takeoff L/D increments for PRA; including aeroelastic effects. Deltas relative to baseline takeoff aileron deflection (7.5°).

B. AFC Structural Weight Increments

For the purpose of conceptual integration trade studies, 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). This approximate analysis approach is appropriate for current scoping of various wing AFC concepts. Further investigations of wing AFC applications should include further structural FEM/Loads/Weight sizing studies using the CFD loading increments. The estimated structural weight penalty is included in subsequent AFC performance assessment. Estimation of incremental systems' weights associated with additional hardware to supply mass flow to the AFC actuators is estimated in a later section.

1. Aileron AFC

Figure 9 summarizes the estimated weight increment to account for wing loading changes due to deeper aileron deflections enabled by aileron AFC relative to the baseline PRA configuration. The spanload changes predicted with deeper aileron AFC deflections [10, 12] increase wing-root-bending moment, and require additional structural material (weight) to accommodate the increased spanloading due to AFC. For AFC applied to aileron deflections of 16°, estimated structural wing weight increases on the order of 0.2 – 0.35% OEW depending on the PR.

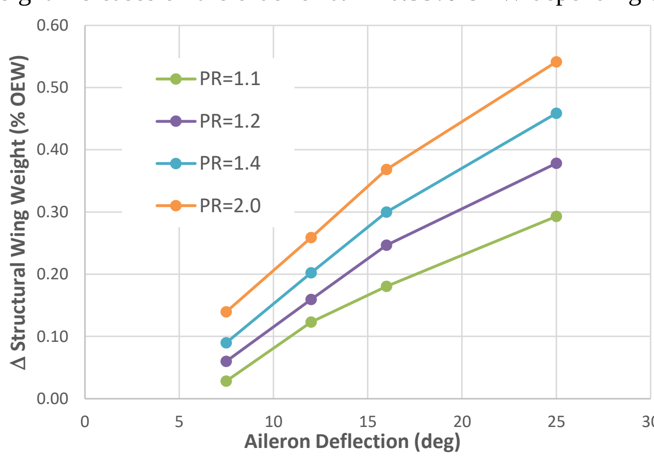

Fig. 9 Aileron AFC: Structural weight increment for modified takeoff wing loading with AFC. Deltas relative to baseline takeoff aileron deflection (7.5°).

2. Wing Leading Edge AFC

Figure 10 summarizes estimated structural weight increases for the AFC application to the nacelle/pylon/wing junction region. (Increments for AFC application to the outboard slat region are contained in Refs.12 and 13.) AFC application to the nacelle/pylon/wing junction region at condition considered has the smallest estimated structural weight impact of the AFC cases considered in current study – less than 0.05% OEW.

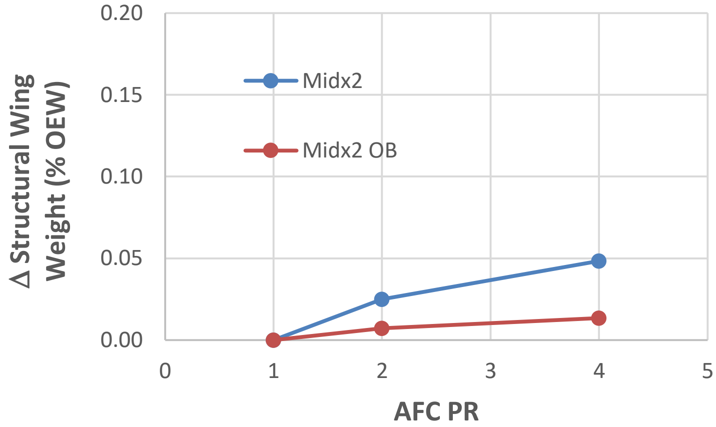

Fig. 10 AFC in Nacelle/Pylon/Wing region: structural weight increment for modified takeoff wing loading with AFC. Deltas relative to baseline takeoff aileron deflection (7.5°).

C. Energy Systems and Integration Considerations

This section provides a summary of several AFC systems configurations studied in detail (see [13]). Multiple sources of flow to the AFC actuators were considered [13] to assess potential performance benefits 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 AFC benefit from each flow source can then be derived by comparing its achievable pressure ratio and flow rate to the required pressure and flow rate for given AFC actuation configuration. The first summarizes potential energy sources for aileron and wing LE AFC applications. Conceptual systems routing and associated installation and weight impacts are estimated for the AFC applications studied. Finally, systems integration challenges and opportunities for assessed AFC energy sources are summarized. Availability/reliability aspects of AFC energy system components were assessed only qualitatively with conceptual considerations of redundancy.

1. Energy Sources

Existing and new energy sources for the reference configuration were assessed for possible AFC actuation during takeoff and initial climb, and/or during final descent and landing phases (see Ref. 13 for additional details):

- 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

The mass flow and PR requirements for studied AFC applications were scaled from the CFD predictions [10-12] to the PRA wing geometry and AFC system layout (including duct losses), as well as to flight conditions (Mach number) for takeoff/initial climb and final descent/landing for the PRA configuration.

As discussed in the subsequent section, generally the APU load compressor can provide the required mass flow and PR (with APU running). Engine bleed could provide adequate flow with suitable pneumatic flow management of other systems (WAI, EAI, A/C packs). A combination 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), however, they could provide sufficient flow to improve aerodynamic performance in certain configurations.

2. Integration of APU Load Compressor for Aileron (Configuration 1)

This configuration takes air from the APU load compressor to power AFC actuators in the fixed trailing edge of the wing embedded along the aileron location as shown in Fig. 11. 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 required mass flows at pressure ratios PR up to 3 – 4 at the aileron station. Use of the APU during takeoffs and landings will likely result in increased maintenance needs for the APU. It is noted that APUs 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 appears feasible with this configuration (in view of failure rates of APU relative to probability of engine out in takeoff).

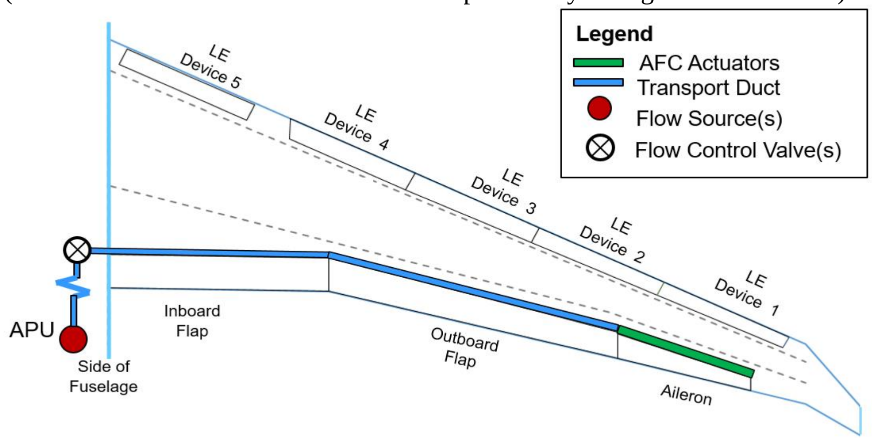

Fig. 11 Aileron AFC: Conceptual Systems Routing from APU to Aileron.

A conceptual schematic for the APU-Aileron AFC systems configuration is shown in Fig. 12. An AFC supply duct branches off 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. 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. The APU air must be kept isolated from the engine bleed air in order to prevent flow reversal into the engine. A parallel AFC valve configuration is conservatively shown to allow for AFC operation in the event that the primary AFC valve fails when the second valve (normally closed) could open to provide flow to the AFC actuators. This layout ensures that both the left wing and the right wing AFC actuators receive equal supply pressure and flow rates to minimize asymmetric aerodynamic AFC performance. Pressure sensors in the left and right wing would monitor and regulate flow in the AFC supply ducts to ensure that both sides are receiving equal amounts of AFC air flow.

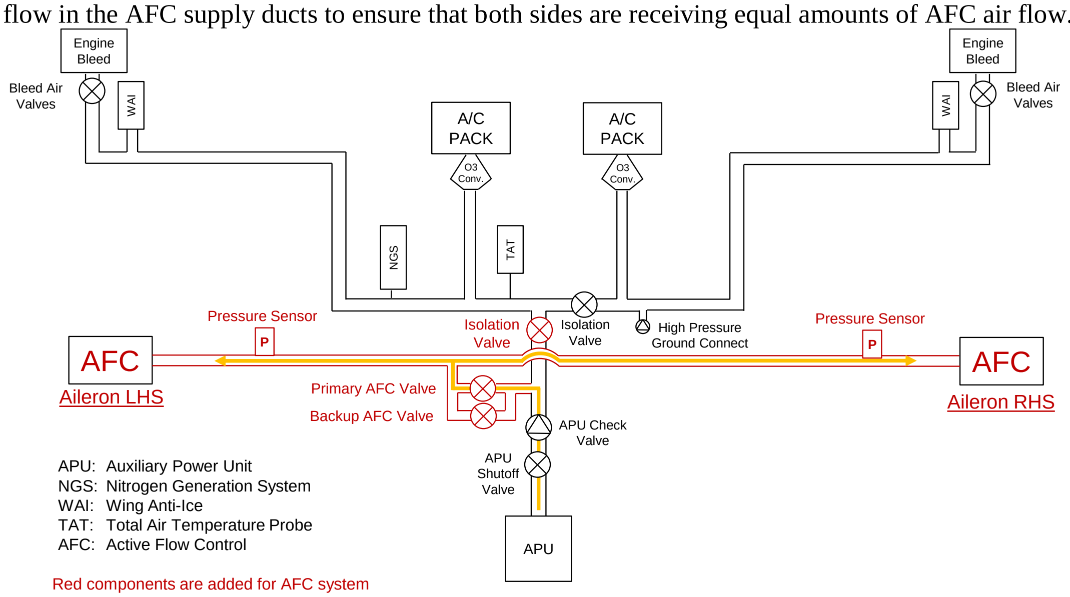

Fig. 12 Aileron AFC: Conceptual system integration of APU routing in baseline pneumatic systems layout.

Figure 13 depicts 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 by typical conceptual wing structure and aileron flight control actuators. Integration of the AFC supply duct(s) around the aileron flight control actuators and routing through wing ribs will be challenging but likely feasible, as is incorporating AFC actuators in that spanwise section of the aileron. The conceptual AFC actuators are embedded in the fixed trailing edge of the wing at the aileron hinge line; the assumed AFC actuators are similar to the '50% nozzle' used in the CFD analysis [10–12] with scaling to the PRA configuration [13].

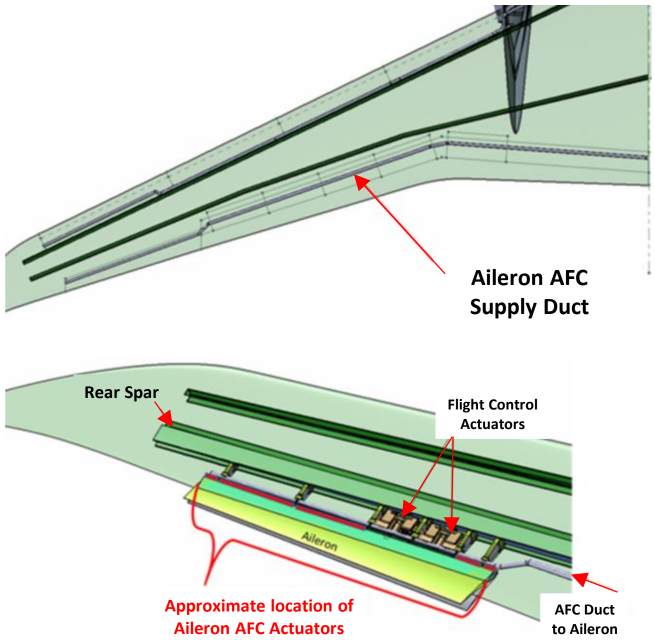

Fig. 13 Conceptual integration of AFC supply duct in wing between fuselage and aileron.

Using the APU load compressor 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 these flight phases. Contrast this to bleed air extraction from the engine, which would penalize engine performance (resulting in larger engine size) to meet takeoff thrust requirements.

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 supplied by 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 altitudes up to the highest takeoff and landing fields while still providing sufficient flow rates to supply AFC flow rates and PRs needed to achieve the significant L/D and $C_{L,max}$ improvements described in Section IV.A.

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 additional systems weight for APU supplied AFC flow ranges from 0.09 – 0.13% OEW for the aileron AFC concept [13].

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 smaller than 10^{-7} per flight hour while a potentially catastrophic event must have an occurrence rate 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 operational at the beginning of the initial phase in the takeoff. The probability of either engine failing during takeoff is $2 \cdot 10^{-6}$ per flight hour multiplied by the time duration of takeoff. Assuming a failure of the AFC system combined with an engine failure during takeoff is potentially catastrophic, the AFC system failure rate should be on the order of $5 \cdot 10^{-4}$ per flight hour or better. The valves, controller, sensors, ducts, and actuators must therefore provide sufficient reliability to meet this requirement [8]. With the current systems technology in use on current airplanes, this is likely achievable with appropriate system architecture [13]. For the current conceptual assessment, it appears that AFC system availability requirements can probably be achieved using available modern technology with appropriate system architecture and mission planning considerations. At this point, it is uncertain how increased in-flight use of the APU would affect its failure rate, if at all. APU maintenance can be expected to increase slightly to mitigate this. A follow-on detailed study is needed to assess APU availability and quantify possible additional APU design and inspection requirements.

3. Integration of Electric Compressor(s) for Aileron (Configuration 2)

Another AFC energy source configuration considered the use of 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 scoping study to assess system-integration feasibility and impacts [13].

The first variation studied (configuration 2a) critically assumes that the airplane's environmental control system is of similar architecture to an existing configuration where cabin air is already 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 existing compressors to provide flow to the AFC actuators is minimal compared to using dedicated AFC compressors. With such all-electric ECS architecture, there would be redundant compressors available to supply the AFC actuators in the event that one ECS compressor failed.

The second configuration (2b) considered uses dedicated (additional) electric compressors powered by the airplane generators to supply to the AFC system - while it is assumed that the airplane has a traditional ECS configuration where engine bleed flow is the ECS pneumatic air source. The dedicated AFC compressor(s) are assumed here to be located 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 AFC compressor(s) [13].

The third configuration (2c) is the same as configuration 2b with the exception that the AFC compressors are assumed 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. Although this is a viable configuration, 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 (or additional battery installed weight] to provide AFC electrical power [13].

4. Integration of APU and Engine Bleed-Air for Nacelle/Pylon/Wing (Configuration 3)

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 Figs. 14 and 17). Ref. 13 provides further details on location and layout of AFC actuators in this application. The APU can plausibly be used to provide AFC air during takeoff and engine bleed can be used during approach and landing. 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.

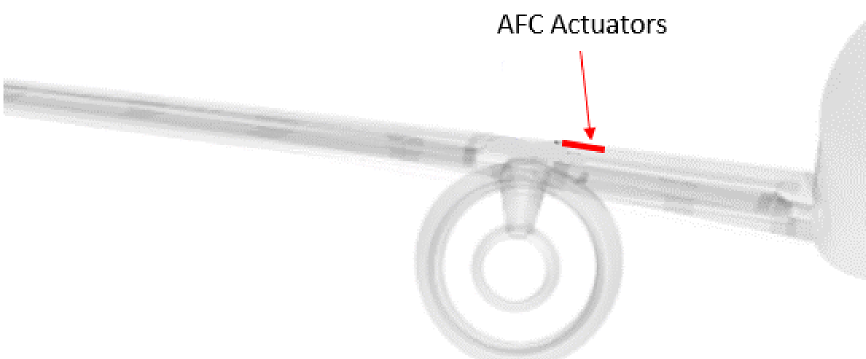

Fig. 14 Nacelle/pylon/wing AFC location (inboard bank of AFC actuators shown).

The main ECS duct may be used to transport the AFC flow to the nacelle/pylon regions. This is a highly efficient configuration since there is only a short new duct 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. A conceptual duct layout of this configuration to supply the AFC actuator(s) is shown in Fig. 15. Figure 16 further 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.

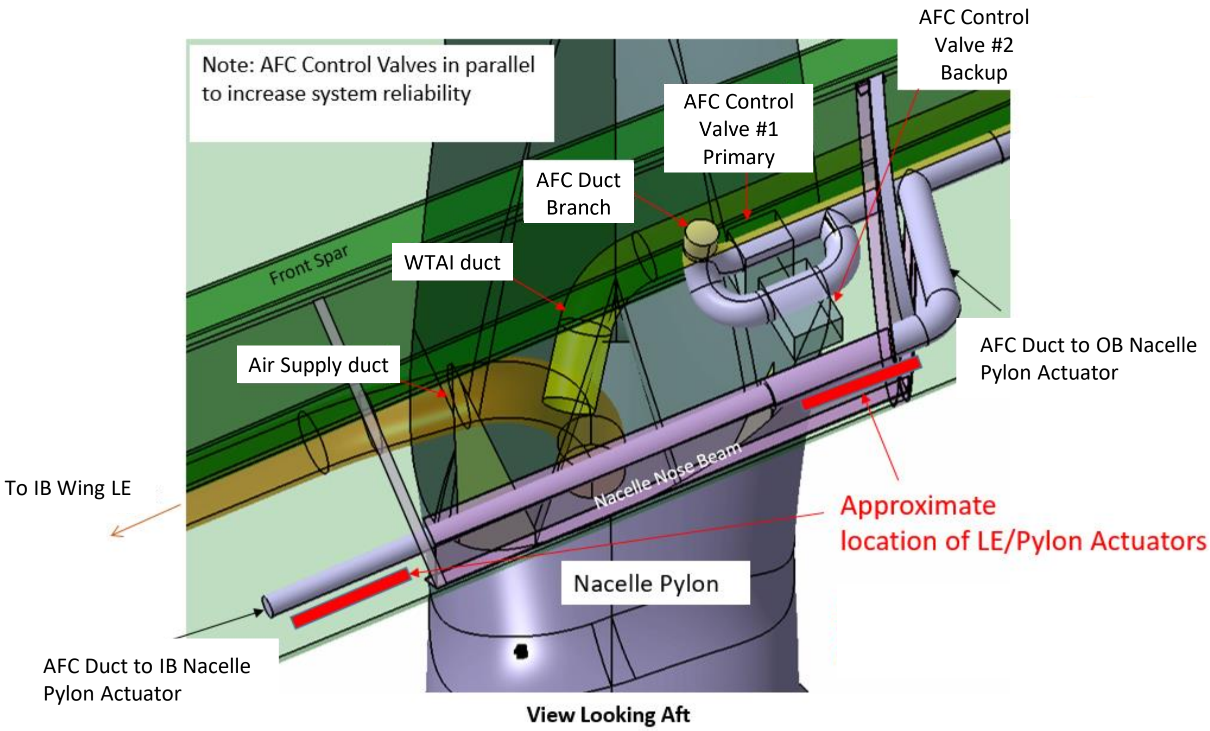

Fig. 15 Schematic duct, valves, and AFC actuator integration near nacelle/pylon/wing junction leading edge.

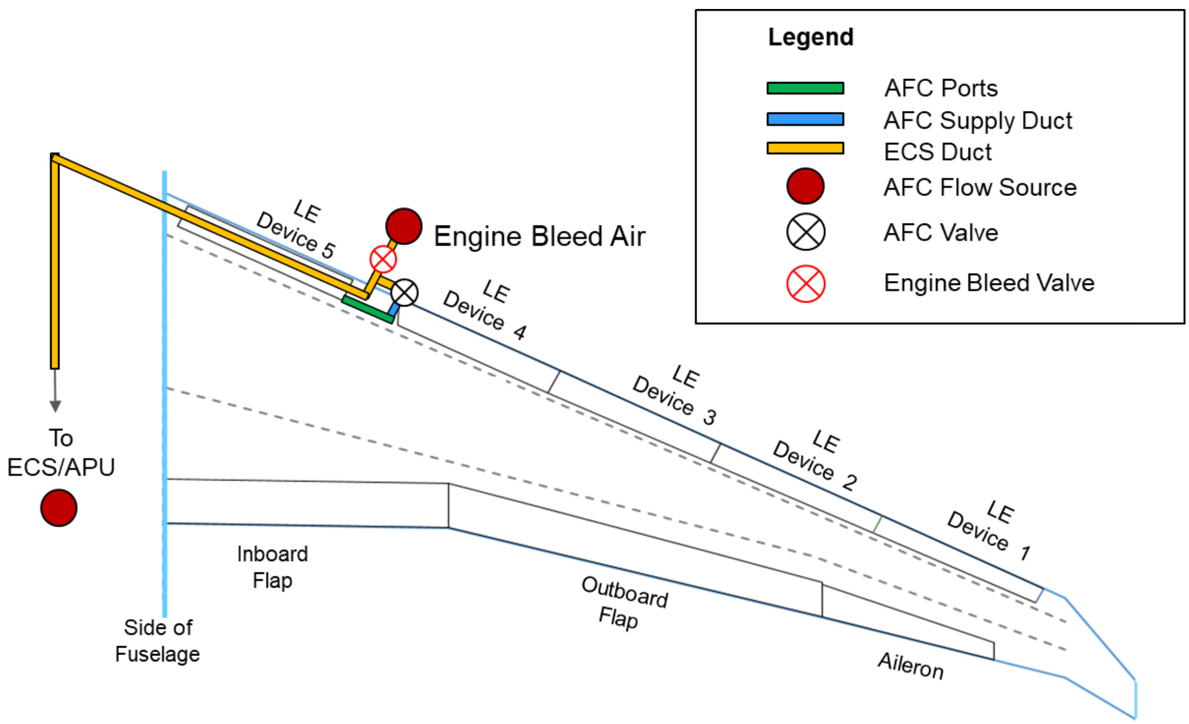

Fig. 16 Nacelle/pylon/wing juncture AFC: Conceptual systems routing from bleed and/or APU.

A notional pneumatic system layout and airflow path is displayed in Fig. 17. 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. From a conceptual systems integration perspective, it appears feasible to incorporate additional ducts, valves and actuators in this leading-edge volume. There are still components in this region such as other valves that may need to be considered but, generally, integration of the AFC actuators close to the source of flow is less challenging compared to the trailing edge aileron integration.

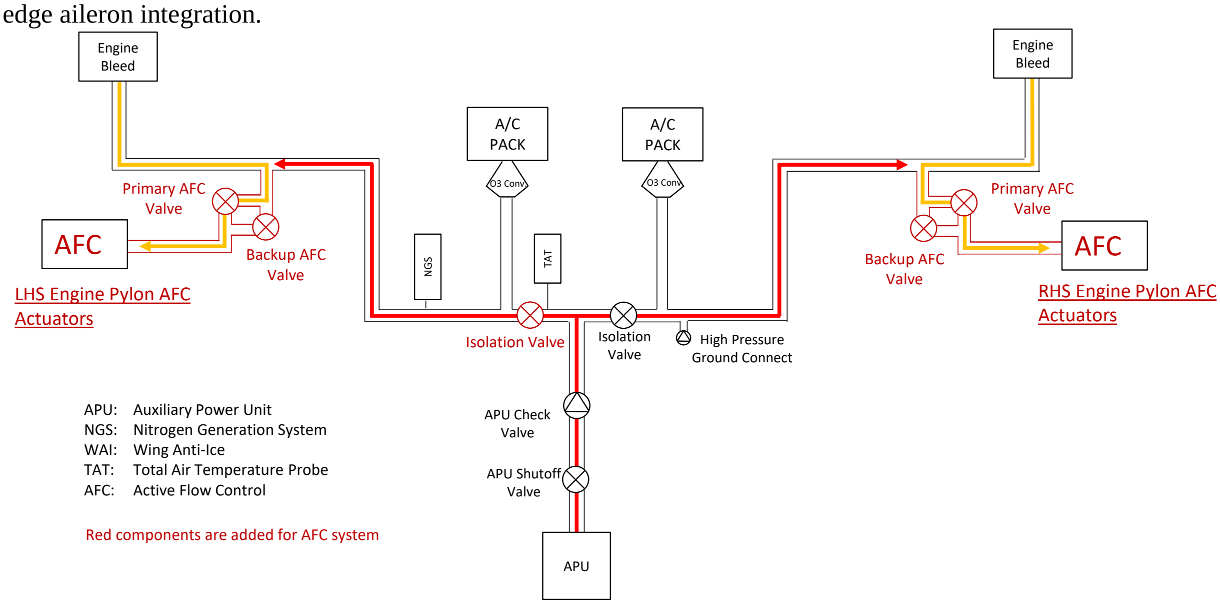

Fig. 17 Leading Edge AFC: Conceptual systems routing from APU or bleed to nacelle/pylon/wing region.

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 failure (or a single side bleed system failure), the APU could be used to supply WAI, AFC, or pack flow to the wing side with the engine failure, while the side with the functional engine and bleed system is separated via the isolation valve. The redundancy lends itself well to this architecture and enhances the reliability of the system in case of a failure in the AFC system. Further discussion on reliability and availability aspects of this system is provided in Ref. 13.

Of the AFC configurations considered, this application has the smallest weight impact. This is due to the minimal amount of additional ducting and valves that is required to supply flow to the actuators in the pylon location of the wing. The system configuration weight increment is approximately 0.05% OEW. 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, pre-cooled engine bleed air would not be available to the airplane's 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 with suitable scheduling of other ECS outputs. Further requirements analysis and availability studies would be needed to assess if temporary deactivation of these systems is acceptable.

5. Summary

Table 1 provides a summary of systems weight and integration challenges of various AFC energy sources scoped in the current study. Table 2 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.

Of the AFC systems configurations studied, the APU with Engine Bleed backup to the LE Pylon AFC had the lowest weight impact because of the proximity of the AFC actuators to the engine bleed/APU duct. The integration of the AFC actuators and ducting at this location was also the least disruptive to structure. The APU to aileron AFC had the second lowest weight impact and is likely a feasible configuration. The major integration challenge of this configuration is routing the AFC supply duct through the wing trailing edge and around the aileron actuator. As described in section IV.C.3, the electric compressor weight penalty is the highest due to extra compressor weight and electrical equipment [13].

Table 1 Summary of weights and challenges of AFC system configurations [13].

Energy Source	Weight Penalty Aileron AFC (% OEW)	Weight Penalty LE Pylon AFC (% OEW)	Key Integration 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	0.01-0.12	0.038	APU Reliability Aileron AFC integration	Possible reliability challenges could be mitigated with bleed air backup
ECS cabin-air compressors	0.12-0.14	N/A	Aileron AFC integration	Requires electric ECS as baseline
Dedicated AFC compressors	0.27-0.51	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	0.31-0.49	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 2 Summary of assessed practicality* of AFC system configurations [13].

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)
Engine Bleed	Scenario dependent	Adequate (Scenario Dependent)	Moderate-High	Minimal	2	3
Auxiliary Power Unit (APU) Load Compressor	Adequate	Likely Adequate (Scenario Dependent)	Moderate	Minimal	3	4
APU with Engine Bleed backup	Adequate	High	Moderate-High	Minimal	4-5	5
ECS cabin-air compressors	Adequate	High	Moderate (if electric ECS is baseline)	Moderate	3	2
Dedicated AFC compressors	Adequate	Likely Adequate (Scenario Dependent)	High	High	2	1

* A score of 5 is the best and 1 is the lowest.

D. Aircraft Level Performance Opportunities

This section summarizes results of conceptual performance integration studies performed for the PRA (Performance Reference Aircraft) to estimate potential airplane-level performance and operational benefits enabled by the localized wing AFC applications discussed studied. Using performance trade factors representative of the PRA configuration, the potential performance opportunities in takeoff and landing for two wing AFC topics are presented here. (The third localized wing leading-edge AFC application concept is discussed in Ref. 13.)

1. Approach for Estimating Net Performance Benefits

Referring to Fig. 1, AFC net aerodynamic increments are combined with structural and systems weight penalty increments to assess integrated aircraft performance opportunities for the PRA project configuration. Within the scope of the current conceptual study of several wing AFC concepts using the most practical energy sources, performance assessments were done utilizing preliminary-design performance trade factors applicable to the PRA configuration. These performance trade factors were derived from 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 aircraft while meeting overall mission payload and range requirements. Where applicable, 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 increment for the nominal PRA economical mission (range and payload). Reference 13 provides further details on the conceptual performance analyses.

Two assessment scenarios were used to scope performance opportunities for wing AFC applications applied on the PRA project aircraft: *sizing* and *nonsizin*g performance scenarios (Table 3). In performance *sizing* scenarios used in the present study, it is assumed that the key aircraft design sizing parameters (wing size, flap area, engine thrust) are varied 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 the key aerodynamic parameter that affects required wing area and engine design thrust needed to meet critical takeoff performance (takeoff climb gradient at engine-out case for high-elevation airports at high air temperature). Improvements in takeoff L/D due to AFC would result in reduced wing area and reduced takeoff thrust (and, related, engine size), reduced aircraft OEW and resulting cruise fuel burn reduction.

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 OEW and cruise fuel burn.

For *nonsizing* performance assessment scenarios, the incorporation of AFC does not affect the key aircraft sizing elements, but AFC, if reliably available, can provide operational benefits to airlines. In particular, for takeoffs from high-hot airports that have gradient limited takeoff climb profiles, L/D improvements feasible with AFC could allow an increase of payload that can be carried by the aircraft from such airports. For takeoff operations with AFC from nongradient-limited airports, the operator could reduce engine thrust during takeoff ('derated' engine thrust setting) to reduce takeoff noise and engine operating costs (e.g., reduced engine maintenance, and/or reduced 'lease-by-hour' fees that are often dependent on engine thrust settings). For the nonsizing takeoff scenario considered here, the key merit of improvement is increase in takeoff payload capability. In current study, this improvement is translated into an estimated life-cycle net value revenue opportunity for airline operations with embedded AFC.

Table 3 AFC performance scenarios and key aircraft design benefits (in bold font).

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

2. Aileron AFC

Selected results are presented for several conceptual performance assessment scenarios with takeoff and landing drooped-aileron AFC on the PRA study configuration. As discussed, application of AFC to drooped symmetric ailerons provides L/D opportunities for sizing with high-hot takeoff constraints that can result in reduced wing area, engine weight and cycled fuel-burn reduction for typical operational range.

Aileron AFC Opportunities for Aircraft with Takeoff Performance as Sizing Constraint

Using trade factor studies for the PRA, the estimated impact of L/D improvement on blockfuel per seat is provided in Fig. 18 for an assumed AFC system weight addition of 0.125% OEW as well as added structural weight for changed wing loading with AFC on ailerons (as discussed earlier). Under the assumptions in this trade study, a significant net improvement potential in blockfuel/seat on order of 0.4 – 0.6% is estimated if high-hot TKO is the critical sizing constraint for the PRA. Aileron deflections above 16° do not provide further blockfuel/seat benefit. Limiting the maximum aileron deflection angle with AFC activated will reduce wing structural weight (which impact on blockfuel changes is included in the analysis underlying Fig. 18), and, hence, reduce manufacturing cost of such airplane. Increasing the AFC systems weight addition above the assumed penalty will reduce the blockfuel/seat benefit, but, depending on the magnitude of systems weight, AFC could still provide a relevant fuel-burn/seat opportunity. The estimated potential fuel-burn improvements enabled by studied aileron AFC are quite significant, and encourage further studies on detailed AFC integration definition and higher fidelity analysis of wing loads and aeroelastic effects.

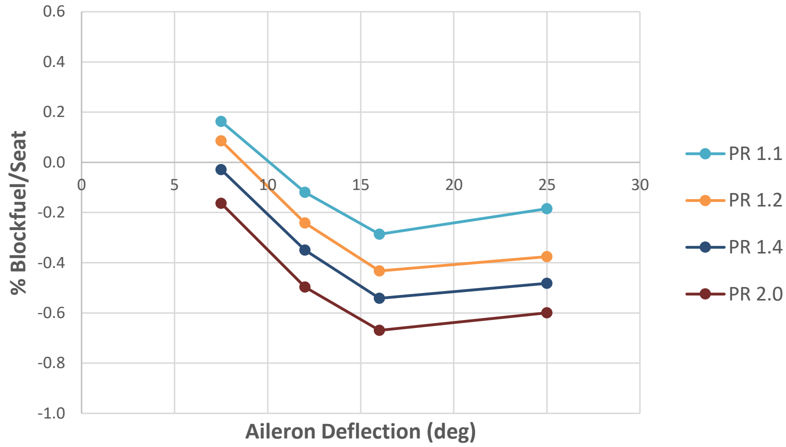

Fig. 18 % Blockfuel/seat change with aileron AFC for aircraft sized for takeoff. AFC system weight 0.125% OEW (APU door drag included).

Aileron AFC Opportunities for Aircraft with Landing Performance as Sizing Constraint

As discussed, deflected aileron (with AFC active) during landing can increase $C_{L,max}$ and reduce approach speed. If V_{app} is sizing the wing and/or flap area, the designer could use AFC in lieu of growing the wing (or flap area, or combination of both). Figures 19 and 20 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 a target V_{app}. An opportunity for 0.1 – 0.25% reduction in fuelburn/seat is estimated with aileron deflections of 12° – 16° under assumed AFC system weight penalty. The increments are smaller in the landing sizing scenario than for the takeoff sizing scenario. If larger symmetric aileron deflections are practical (in view of roll control requirements), the landing scenario predicts larger AFC increments up to 0.3% for higher PR considered.

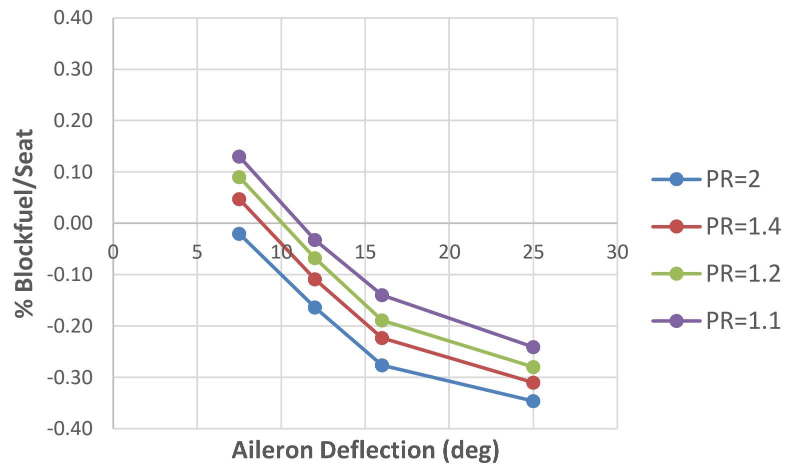

Fig. 19 % Blockfuel/seat change with aileron AFC (landing wing size trade to maintain V_{app}). AFC system weight 0.125% OEW (APU door drag included).

A fuel burn alternate to increasing the overall wing area to reduce approach speed, the designed could enlarge the flap area relative to the (fixed) wing 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 smaller than for the wing-sizing landing scenario. Figure 20 indicates that even with the nominal AFC aileron system weight penalty of 0.125% OEW, there is no net AFC benefit under this landing sizing scenario.

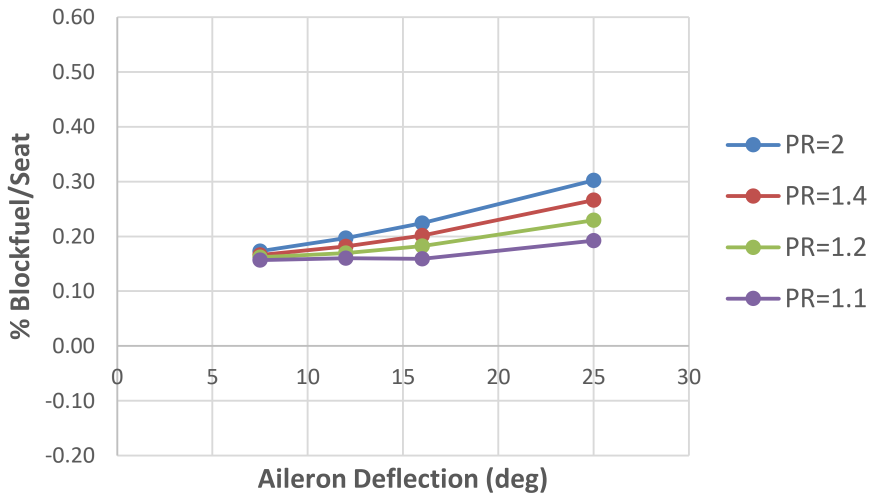

Fig. 20 % Blockfuel/seat change with aileron AFC (landing flap area size trade to maintain V_{app}. AFC system weight 0.125% OEW (APU door drag included).

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

In this performance 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 sizing of the performance reference aircraft; however, AFC could favorably 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. A benefit assessment was done using approximate airline lifecycle value benefit analyses.

Table 4 summarizes estimated takeoff performance opportunities for aileron droop with AFC at PR1.4 for gradient-limited takeoffs (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 4 also indicates the adverse impact of adding AFC structural and systems weight to the aircraft, resulting in a small increase in block fuel needed to complete the baseline mission. For shorter-range aircraft, the operational impact of such related increased cruise fuel burn is relatively minor – only slightly reducing the overall life-cycle value of the aileron AFC incorporation.

Table 4 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 airline operations are gradient limited and AFC would allow payload increases as indicated in Table 4 for those flights. The remaining 75% of takeoffs are not gradient limited, and are assumed to benefit from engine takeoff thrust derating. An estimated penalty for increased maintenance (APU systems) is included in the life-cycle estimation. Figure 21 indicates that with current study assumptions a significant increase in net life-cycle airline value can be expected: on the order of several M$ per airplane over its operational service 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 cost of an aircraft equipped with an AFC system. These cost estimates are included in the life-cycle analysis [13].

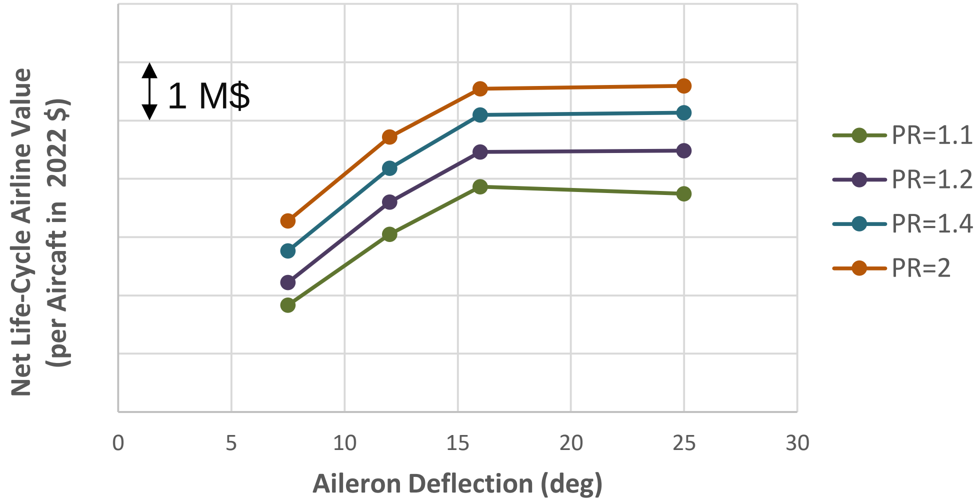

Fig. 21 Estimated life-cycle operator value for aileron AFC in operational use for assumed fraction of gradient limited takeoffs.

3. Wing Leading Edge AFC

Selected results are presented for assessments of takeoff performance opportunities with AFC incorporated in the nacelle/pylon/wing leading edge. Reference 13 provides estimated performance increments for the outboard slat localized AFC application on the outboard wing leading edge [11,12].

The takeoff performance sizing scenario for the nacelle/pylon/wing application was assessed with the AFC layout considered in Section III.C.4 (APU/bleed combined). The performance improvement with AFC provides a takeoff L/D benefit that translates into a blockfuel/seat sizing increment up to 0.2% for higher PRs (Fig. 22).

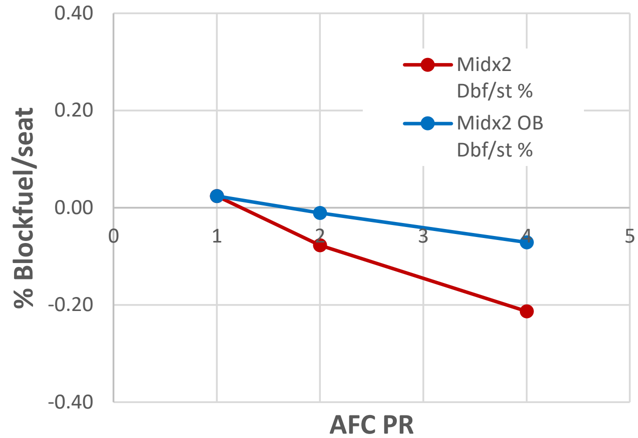

Fig. 22 % Blockfuel/seat change with Nacelle/Pylon/Wing AFC for aircraft sized for takeoff (APU/Bleed AFC system weight and APU door drag included).

Available (preliminary) CFD results on the CRA configuration in the landing configuration with nacelle/pylon/wing region AFC actuation suggest a potentially significant increase in $C_{L,max}$. Results are for initial nonoptimized AFC actuator positions in this region with complex flows. It is reasonable to expect that the predicted improvement for the CRA can translate to relevant $C_{L,max}$ (and $C_{L,app}$) opportunities for the PRA configuration. Based on the takeoff performance potential estimated for AFC on the aileron (Fig. 22), a material fuel-burn landing opportunity with nacelle/pylon/wing AFC may exist. Further CFD and performance studies are needed to quantify landing performance opportunities with optimized nacelle/pylon/wing AFC concepts under both sizing and nonsizing scenarios.

4. AFC Performance Considerations

The localized wing AFC applications topics studied here at a conceptual integration level point to potentially relevant net performance opportunities for the PRA configuration – under assumptions of current analysis. The integration scoping study focused on characterization of AFC concepts first explored in the CFD studies [11-12]. Of the localized concepts studied [Ref. 13], the drooped aileron application appears to provide the most significant takeoff net sizing performance opportunities. AFC in the nacelle/pylon/wing region provides a smaller takeoff opportunity – but may provide a more sizeable benefit for the landing configuration – if substantiated in future CFD studies. The wing leading edge application near the outboard slat close to the wing tip was explored in CFD studies [10–12] for the CRA takeoff configuration; it is possible that flow-control benefits are available in the landing setting with a gapped slat. High-aspect-ratio wings with small chords have limited volume available for routing AFC ducts or to integrate small electrical compressors. Detailed further study of current (and possible other) localized wing AFC applications are needed to enhance understanding of AFC net performance opportunities and integration challenges.

5. Comparison to Previous Non-Wing AFC Application Study

Conceptual integration trade results for localized wing AFC applications considered in current study can be compared to previous AFC integration studies on the vertical fin/rudder of a medium-sized passenger aircraft [8]. 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, to allow reduced cruise drag and OEW, while satisfying rudder/fin stability and control requirements [8]. Assuming the same performance sizing trade factors as used in current wing AFC study, and assuming the same cruise drag, SFC and weight impacts due to AFC on the vertical fin as used in Ref. 8 ('most likely' estimates for the sweeping-jet AFC system in Table 4 therein) also apply to the PRA configuration, the sizing performance benefit for AFC applied to a PRA vertical fin/rudder could be a 0.2 - 0.25% reduction in blockfuel/seat. The localized wing aileron AFC topic summarized in this paper suggests a potentially larger integrated performance benefit than the vertical fin/rudder AFC application. It is noted that current conceptual studies of localized wing AFC opportunities were less detailed in scope than the vertical-fin/rudder application studies in Ref. 8.

V. Concluding Remarks

A conceptual integration and performance 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 impacts and resulting potential net performance opportunities. The conceptual study focused on the use of AFC over deeper symmetrically deflected ailerons, or application to selected wing leading edge regions, to enhance low-speed takeoff and landing performance. Most efforts in the current study were directed at quantifying possible aileron AFC opportunities and challenges.

AFC applied to deeper deflected symmetrically drooped ailerons during takeoff are estimated to allow a 2 – 5% potential net gain in aircraft L/D (including assessed trim and aeroelastic/structural impacts). The required energy (pneumatic mass flow and PRs of 1.4 – 2) to power localized AFC could probably be supplied by existing onboard systems (APU load compressor and/or engine bleed air) with modest system weight penalty. Novel supply architecture, such as compressors (possibly powered by high-voltage/high-density batteries) may be suitable for certain localized wing AFC applications – but only if the baseline aircraft systems architectures is already electrical. Current APU load compressors have capacity to provide energy for the local wing AFC concepts studied on the reference aircraft. Availability of the APU/bleed-air energy sources for AFC during takeoff and/or landing conditions is likely adequate, but would need further detailed FHA studies (beyond the scope of current scoping studies).

Using the estimated integration penalties, an aileron AFC application could provide up to 0.5% blockfuel/seat performance improvement for deeper-drooped aileron deflections if AFC is used to mitigate the high-hot takeoff sizing constraint. Increasing aileron deflection with AFC over 16° in takeoffs does not provide further integrated performance benefit. Recognizing some uncertainty in AFC related weight increments estimated in current studies, it is possible that a practically integrated aileron AFC at available PR's and mass flows could provide 0.2–0.4% net blockfuel/seat opportunity if take-off high-lift constraints are sizing the configuration. Furthermore, for the considered wing-sizing landing scenario, aileron AFC in landing could potentially provide 0.2–0.3% blockfuel/seat opportunity if AFC is used to mitigate V_{app} constraints.

For the nonsizing performance scenarios considered, 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 options (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 allow significant life-cycle value benefits to airline operators with aircraft equipped with aileron AFC.

In addition to aileron applications, AFC enhancements to localized wing leading edge regions were conceptually studied. One wing leading edge concept addressed AFC actuation in the nacelle/pylon/wing junction. CFD available for takeoff conditions suggests relevant L/D increments and significant increases in C_L at alpha and $C_{L,max}$, particularly at higher PRs: AFC applied to the nacelle/pylon/wing region could provide a 0.1 – 0.2% potential integrated net blockfuel/seat performance gain (takeoff sizing scenario) due to L/D improvement in 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 possible this AFC application can translate to relevant $C_{L,max}$ enhancement with resulting net (sizing) landing performance opportunity for a PRA type configuration.

Another wing leading-edge AFC application topic considered was in upper-surface outboard wing leading edge near the slat when deployed in a takeoff setting. Available CFD study results suggest relevant L/D increments and a modest increase in C_L at alpha with AFC in takeoff using higher PRs. In takeoff, such AFC application near the outboard slat could provide 1.5 – 2.0% potential performance gain in L/D for available AFC mass flow at PRs 2 – 4 from existing onboard systems (APU and/or bleed air). With the assessed systems and structural weight impacts for the AFC system, a small (~0.1%) fuel-burn/seat performance benefit resulted for the takeoff sizing scenario for this application. However, further understanding of aerodynamic and flow physics effects underlying the predicted slat AFC increments is recommended - as they may point to increased aerodynamic opportunities.

The current results suggest that the energy to power AFC (mass flow at required PRs) for the studied localized wing application topics could generally be supplied by already existing onboard systems (but extra ducting and systems hardware are required). In particular, the APU load compressor operated during takeoff (and landing) can generally meet the AFC energy requirements for the wing applications scoped. It also appears likely that an operational APU can power AFC with adequate availability for the critical engine-out takeoff case. Detailed FHA studies are needed to confirm adequate APU availability/reliability in takeoff and landing cases where AFC enhances critical aerodynamic performance. The current study showed that the APU is a potentially attractive existing energy source for local wing AFC with relatively moderate systems weight implications. Bleed air could be used as the primary AFC flow source during landing with proper mission planning and managements of pneumatic flow systems (WAI, EAI, A/C Packs). Engine bleed air can be used as a backup flow source to supplement APU air when engine thrust reduction is too detrimental to be traded against providing primary AFC flow source during takeoff.

This study addressed key conceptual spatial integration aspects of AFC actuators, ducting, and pneumatic control systems for several localized wing AFC application topics considered. Integration of AFC ducts in the wing trailing edge and wing trailing edge overall appears conceptually feasible, but installation of AFC ducting and AFC actuators near the aileron actuation systems is expected to be challenging but not impossible, in particular on smaller aircraft. On the other hand, proximity of existing pneumatic ducting in nacelle/pylon/wing junction region could greatly reduce added systems weight for the AFC application in this region. Relative to the outboard wing leading edge AFC concept, the nacelle/pylon/wing region has fewer spatial integration challenges.

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