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AFC-Enabled Vertical Tail System Integration Study

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March 2014

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Report Description:

This document serves as the final report for the SMAAART AFC-Enabled Vertical Tail System Integration Study. Included are the ground rule assumptions which have gone into the study, layouts of the baseline and AFC-enabled configurations, critical sizing information, system requirements and architectures, and assumed system properties that result in an NPV assessment of the two candidate AFC technologies..

This document satisfies Deliverable Items 4.4, 4.5, 4.7 and 4.8 in the Task Order NNL10AD24T, Reference (1), while incorporating Deliverable 4.3 (completed March 30, 2011).

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Nomenclature

- β sideslip angle
- δ_r rudder deflection
- A_j area of jet exit (orifice)
- AFC active flow control
- APU auxiliary power unit
- ARP Aerospace Recommended Practice
- $c/4$ quarter chord (25% chord)
- C_μ momentum coefficient
- C_b blowing ratio
- C_n yawing moment coefficient
- C_l rolling moment coefficient
- C_Y side force coefficient
- CFD computational fluid dynamics
- CG center of gravity
- CMO Boeing's Current Market Outlook
- DOF degrees of freedom
- EO engine out
- ERA Environmentally Responsible Aviation
- FAR Federal Aviation Regulations (Code of Federal Regulations, Title 14)
- FBW fly-by-wire
- FCC flight control computer
- FCM flight control module
- IFSD in flight shut down
- LE leading edge
- LRU line replaceable unit
- MAC minimum acceptable control
- MC marginal unit cost
- NPV net present value
- Q quantity of units built
- SME subject matter expert
- t/c airfoil thickness to chord ratio
- TO take off
- TFU theoretical first unit recurring cost
- TRU transformer/rectifier unit
- U_j jet velocity
- V_1 takeoff decision speed for engine failure
- V_2 takeoff safety speed
- V_{MCA} takeoff minimum control speed, air
- V_{MCG} takeoff minimum control speed, on ground
- V_{MCL} landing minimum control speed, air
- V_R takeoff rotation speed
- V_{SR} reference stall speed
- WACC weighted average cost of capital

1. Introduction

As part of the Environmentally Responsible Aviation (ERA) Project, NASA is seeking to demonstrate the potential benefits of reducing vertical tail size through the use of active flow control (AFC). An AFC-enabled vertical tail would utilize AFC to provide required performance at flight conditions that drive the sizing of the vertical tail while operating in a conventional manner at all other flight conditions.

AFC has been successfully demonstrated to increase the lifting force of aerodynamic surfaces via separation reduction at various scales and for various configurations. However, the airplane-level benefits, as well as the system integration and flight requirements for these AFC systems, have not been sufficiently investigated to mature the technology to flight. NASA is seeking to evaluate the relative merits of selected AFC systems within the framework of the ERA program goals regarding noise, nitrous oxide emissions, and aircraft fuel burn.

In collaboration with NASA, Boeing has initiated a system integration study that will examine the challenges associated with integrating zero-net (synthetic jet) and positive-net (sweep jet) mass flux AFC actuators into the vertical tail of a commercial aircraft and assess the net value of these configurations to the airplane.

The system integration study starts by establishing the baseline airplane configuration against which the AFC-enabled vertical tail configurations will be weighed. The AFC-enabled configurations selected for this study will be based on a certain level of (unvalidated) AFC aerodynamic performance, with the vertical tail and aircraft systems sized accordingly. The actual use of AFC technologies remains to be validated through demonstrating that the required vertical tail performance can be achieved and that there is net value in the implementation of the system through cost / benefit modeling.

A review of the relevant vertical tail characteristics that contribute to aerodynamic performance is provided, along with FAR requirements and other design drivers that are expected to size vertical tails. A description of tail-sizing is provided, in the context of the performance that the AFC-enabled vertical tails are required to provide. The design drivers that are established allow the key operating conditions to be defined.

Functional requirements for the AFC system are established, allowing the AFC systems to be architected and integrated into the systems and vertical tail. Architectures for both synthetic jet and sweep jet actuators are developed and integrated into the systems and vertical tails. Since the integration study is performed using an assumed level of AFC performance, trade studies are performed based AFC system power requirements to understand limitations and challenges associated with integrating a wide range of AFC actuators into the vertical tail and airplane systems. This provides a range of AFC system characteristics to use in the evaluation of the benefit of the system to an airplane fleet.

A net present value (NPV) approach is used to assess the relative merits of these AFC systems. The calculated NPV is a summation of all of the positive and negative impacts of implementing a given technology on an airplane or family of airplanes relative to a baseline scenario. These might include incremental impacts on non-recurring and/or recurring cost, weight, performance, maintenance, among others. These impacts are monetized using trade factors and time adjusted from when they occur to present day (or specified date) dollars. The result allows different technologies or different ways of implementing a given technology to be compared on an equivalent basis. It is a primary

consideration when determining whether or not to expend the resources to develop and implement a technology on an aircraft design. The basic structure of the NPV tool that is utilized is described, as are some of the assumptions that are required to carry out the NPV evaluation. Concluding the system integration study is a discussion of recommendations for future development, including guidance for future wind tunnel and flight testing, as well as technical challenges discovered throughout the course of the study.

This study is not intended to be a detailed design exercise. The intent is to bring forward the issues associated with integrating such AFC systems on a commercial airplane and attempt to quantify their impact. Many assumptions are made along the way. Where possible, the sensitivity of the results to varying these assumptions is explored. Some remain and contribute uncertainty to the results.

It should also be noted that this study does not attempt to determine the optimal AFC configuration from a performance enhancement perspective, whether it be the number of actuators, their spacing, their configuration or the amount of energy supplied to each in the form of pressurized air or electrical power. These are the subject of numerous other studies. Instead, a range of scenarios is evaluated here. It is expected that the results herein can help determine which combinations of system characteristics are required to produce an implementation that adds net value to an airplane as well as potentially highlight combinations that might represent more efficient or higher value approaches. It also highlights areas that are deemed critical to a successful implementation that may be underemphasized in research to date and provide motivation for them to get more attention in the future.

2. AFC Technologies and Airplane Family for Technology Application

2.1. AFC Technologies

Active flow control can be defined as the commanded manipulation of fluid flows with the addition or subtraction of energy from the fluid. AFC facilitates both off-condition optimization and the ability to react to sudden changes in flow conditions. The single function of AFC in this project is to prevent/delay boundary layer separation on the rudder to increase rudder aerodynamic effectiveness to facilitate down-sizing of the vertical tail. It is important to note that the intent is to prevent or delay separation as opposed to attempting to re-attach the boundary layer after separation.

Two types of AFC actuators are studied here for potential application – synthetic jets and sweep jets. Both technologies produce an oscillating jet of air and act to reduce flow separation on the control surface. Sub-scale testing has shown that placing the actuators upstream but near the location of natural separation on the aerodynamic surface produces substantial control surface effectiveness increases. Placement of the actuators just ahead of the rudder hinge line is assumed for this study.

The synthetic jet used in this study functions with a piezoelectric disc that oscillates in an enclosed cavity, ingesting and expelling air through an orifice, as seen in Figure 1, adapted from Reference (2). The specific actuator design for the synthetic jet used in this study is created by a piezoelectric ceramic disk clamped and sealed over a cavity and orifice, as seen in Figure 2. The piezoelectric disks are driven by an electric power source and a function generator, allowing the piezoelectric disks to be driven at specific frequencies and to employ pulse modulation. The oscillating motion of the piezoelectric disk alternately ingests air at the edge of the orifice and expels it out the center of the orifices, creating a pulsing or oscillating flow, as depicted below. Since these

actuators draw on the flow of the free-stream air to create the jet and no mass is added to the flow, these actuators are also referred to as zero-net mass flux actuators.

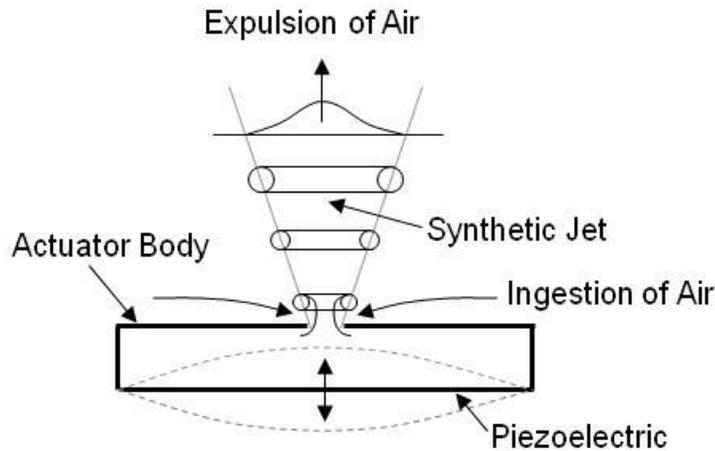


Figure 1: Synthetic Jet Actuation, Ref. (2)

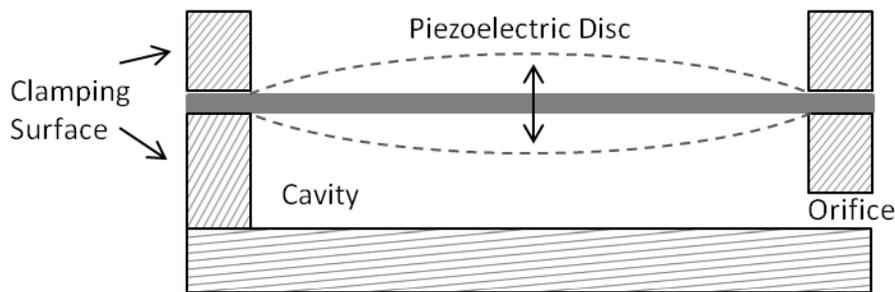


Figure 2: Synthetic Jet Components

A sweep jet is an AFC device that draws pressurized air from a plenum or manifold through an actuator body and out an orifice to create an oscillating flow. A pressurized air source is required to power these AFC actuators. A schematic of the actuator body, from Reference (3), is shown in Figure 3. An illustration of jet that is created is shown in Figure 4, from Reference (4). Both instantaneous and time-averaged images of the jet are shown. The oscillation is set up as the air moves through the interaction region and feedback paths of the actuator body and establishes a bi-stable jet that attaches to either sidewall of the diffuser outside of the orifice. Due to the use of a pressurized air source, these actuators are also referred to as positive-net mass flux actuators.

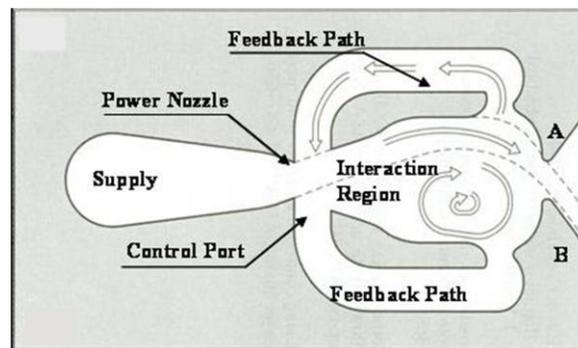


Figure 3: Sweep Jet Actuator Body, Ref (3)

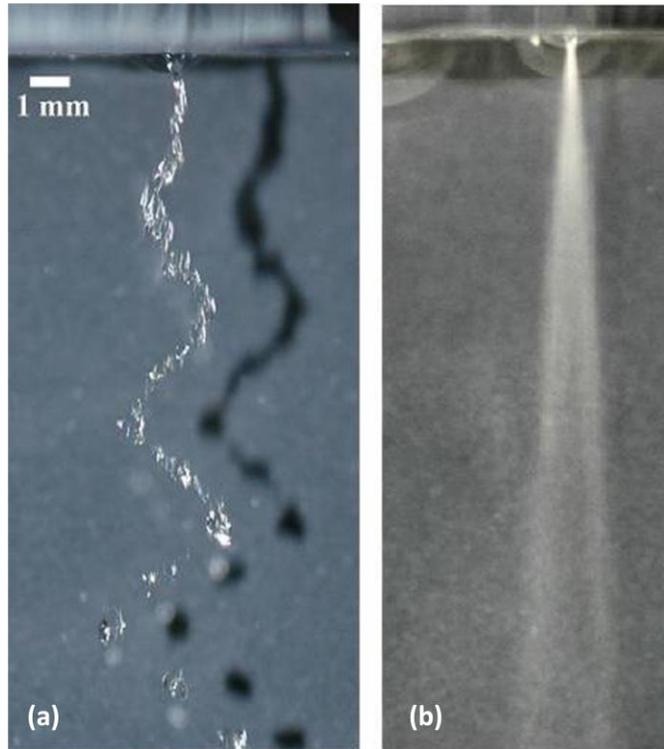


Figure 4: (a) Instantaneous and (b) Time-averaged Sweep Jet Actuation, Ref (4)

2.2. Airplane Family for AFC Technology Integration

The baseline and AFC-enabled rudder airplanes will be representative mid-size twin engine three-member airplane families, with the shortest and longest members of each family used to bracket the vertical tail study. Each family, both baseline and AFC-enabled, will be assumed to employ the same size vertical tail within their respective family members.

The baseline family's vertical tail will be sized based on the shortest family member, as is typically done. The AFC-enabled vertical tail will be sized based on the study airplane's longest family member, as seen in Figure 5, with any vertical tail performance shortfall experienced by the shorter members of the family assumed to be compensated with AFC technology. This method allows the vertical tail on the longest member of the AFC-enabled family to work as a conventional stabilizer, with no AFC needed to maintain full performance capability. Preliminary design techniques were used to establish the resulting relative tail sizes between the baseline and AFC-enabled families. This resulted in the AFC-enabled tail being 17% smaller than that of the baseline. Conversely, the baseline tail is approximately 20% larger than the AFC-enabled one.

Sub-scale wind tunnel results for AFC-enabled vertical tails indicate that sufficiently large vertical tail and rudder effectiveness benefits are achievable to support this assumed tail size difference, References (3) & (5). The vertical tail sizing criteria described in Section 3 will be used to set performance and power requirements for the AFC system based on the assumed tail size of the study airplane family.

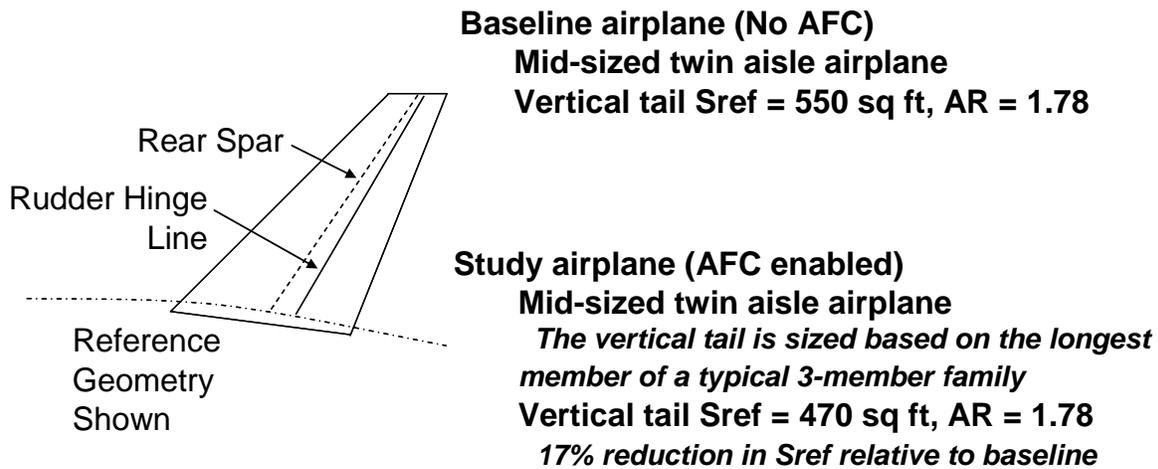
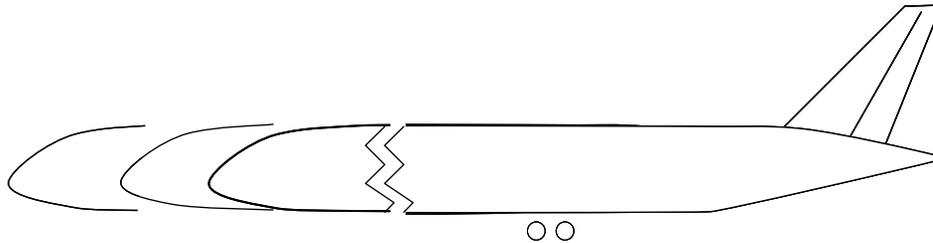


Figure 5: Baseline and AFC Study Airplane Families.

3. Vertical Tail Sizing

3.1. Vertical Tail and Rudder Characteristics

Vertical tail geometric characteristics include planform (leading edge sweep, aspect ratio, and taper ratio), thickness (thickness-to-chord ratio, (t/c)) and rudder-chord to vertical-tail-chord ratio. Each of these characteristics is a trade between aerodynamic efficiency and performance, structural weight, and internal system requirements. Historical precedent and experience drive the complete integrated airplane design. Basic aerodynamic performance of the vertical tail is a function of airfoil characteristics, e.g. t/c , leading edge radius and $c/4$ sweep. These characteristics are assumed to be consistent between the baseline and study airplanes.

The degree of directional stability and control provided by the vertical tail is proportional to the size of the vertical tail and its distance from the aircraft CG. The vertical tail size is the only characteristic that is varied between the baseline and study airplanes, as defined above.

3.2. Tail Sizing Criteria and Constraints

Vertical tails are sized to meet federally mandated requirements and airplane performance requirements, including takeoff and landing field length capability and crosswind capability. The federally mandated requirements that are relevant to vertical tail sizing through airplane performance and handling qualities are compiled below from Reference (6):

- FAR25.107: Takeoff Speeds. This section specifies that V_2 may not be less than $1.1 \cdot V_{MCA}$ and that V_R may not be less than $1.05 \cdot V_{MCA}$, and V_1 may not be less than V_{MCG} plus the speed gained while the pilot recognizes a dynamic engine-failure during a takeoff roll.
- FAR25.125: Landing. This section specifies that V_{REF} may not be less than V_{MCL}
- FAR25.147: Directional and Lateral Control.
 - FAR25.147a: *Directional Control*. “It must be possible, with the wings level, to yaw into the operative engine and to safely make a reasonably sudden change in heading of up to 15 degrees in the direction of the critical inoperative engine. This must be shown at $1.3 \cdot V_{SR1}$ for heading changes up to 15 degrees.”
 - FAR25.147e: *Lateral Control, All Engines Operating*. “There must be enough excess lateral control in sideslips (up to sideslip angles that might be required in normal operation), to allow a limited amount of maneuvering and to correct for gusts.”
- FAR25.149: Minimum control speed
 - FAR25.149(e): V_{MCG} “The minimum control speed on the ground...the calibrated airspeed during the takeoff run at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane using the rudder control alone (without the use of nosewheel steering)...”
 - FAR25.149(b),(c): V_{MCA} “The calibrated airspeed at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane with that engine still inoperative and maintain straight flight with an angle of bank of not more than 5 degrees.” ; “may not exceed $1.13 \cdot V_{SR}$ ”
 - FAR25.149(f): V_{MCL} “The minimum control speed during approach and landing with all engines operating, is the calibrated airspeed at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane with that engine still inoperative, and maintain straight flight with an angle of bank of not more than 5 degrees.”
 - FAR25.149(h): “In demonstrations of V_{MCL} , ... lateral control must be sufficient to roll the airplane, from an initial condition of steady flight, through an angle of 20 degrees in the direction necessary to initiate a turn away from the inoperative engine, in not more than 5 seconds.”
- FAR25.177: Static lateral-directional stability
 - FAR25.177(c): “In straight, steady sideslips, the aileron and rudder control movements and forces must be substantially proportional to the angle of sideslip in a stable sense; and the factor of proportionality must lie between limits found necessary for safe operation throughout the range of sideslip angles appropriate to the operation of the airplane. At greater angles, up to the angle at which full rudder is used or a rudder force

of 180 pounds is obtained, the rudder pedal forces may not reverse; and increased rudder deflection must be needed for increased angles of sideslip...”

- FAR25.181: Dynamic stability
 - FAR25.181(b): “Any combined lateral-directional oscillations ("Dutch roll") occurring between $[1.13 \cdot V_{SR}]$ and maximum allowable speed appropriate to the configuration of the airplane must be positively damped with controls free, and must be controllable with normal use of the primary controls without requiring exceptional pilot skill.”

Some of the above FARs have direct tie-ins to vertical tail characteristics and sizing, while others are more indirect through airplane performance characteristics. For example, the certified minimum control speeds (V_{MCG} , V_{MCL} , V_{MCA}) impact takeoff and landing performance through their relationship to the takeoff and approach speeds (V_1 , V_R , V_2 , and V_{REF}). If the reduced tail size results in the minimum control speeds limiting takeoff and landing speeds, takeoff and landing field lengths or payloads are negatively impacted.

One additional requirement not addressed in the FARs is crosswind capability. The FARs require that crosswind capability be demonstrated, but do not provide a performance target to be used in tail sizing. Crosswind capability is typically driven by customer expectations; airlines expect to be able to operate their airplanes in conditions even with significant crosswinds.

The FARs and performance implications discussed above are tied to the airplane-level yawing moment capability in different regimes of the rudder (δ_{rud}) and sideslip (β) dataspace, as shown in Figure 6. Of the regimes highlighted, it is the minimum control speed (engine-out) regime that is critical for the application of AFC to a vertical tail, as raw yawing moment capability is required from the AFC system to maintain the capability of the baseline vertical tail. The other areas associated with aircraft stability, large sideslips, and crosswinds are deemed not critical with the application of AFC.

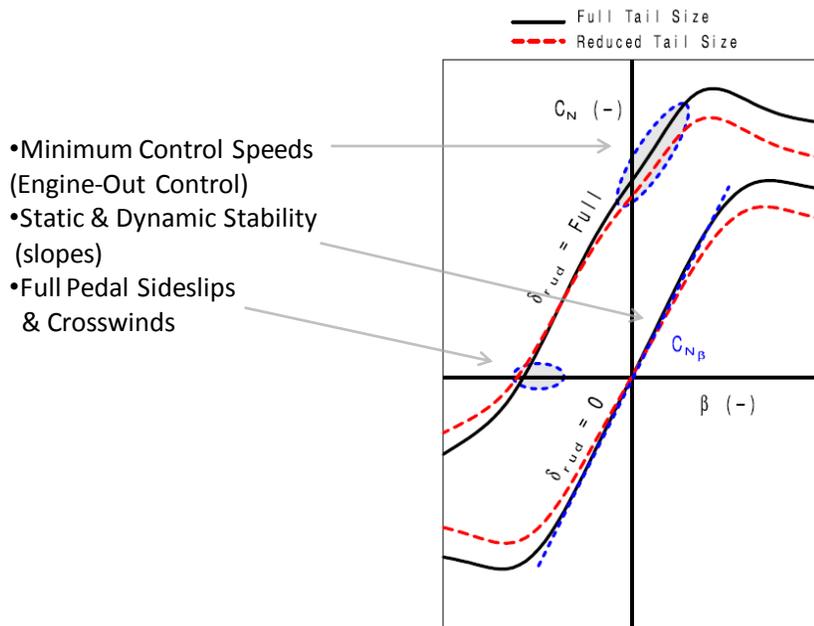


Figure 6: Summarized Tail Sizing Conditions

With the engine-out conditions identified as the critical design conditions for vertical tail performance, performance targets for AFC effectiveness can be set. Defining the yawing moment requirements requires an understanding of the thrust characteristics, takeoff and landing performance requirements, and other stability and control characteristics of the airframe. Defining these for the baseline airplane is beyond the scope of this study, but establishing the AFC effectiveness performance targets can be done without them. Assuming that the baseline airplane has a vertical tail that is sized to just meet the most critical vertical tail sizing requirement, any shortfall in airplane-level yawing moment capability at the critical sideslip and rudder combinations must be compensated for by the application of AFC. For the purposes of this study, a review of current airplane designs was conducted and a representative critical sideslip range of 0 to 8° was chosen.

Maintaining the airplane-level yawing moment capability is analogous to maintaining side-force capability of the vertical tail and rudder. This approach can be written into the relationship shown in Equation 1:

$$\frac{Y_{AFC}(\beta = \beta_{crit}, \delta_{rud} = \delta_{rud_{max}})}{Y_{NoAFC}(\beta = \beta_{crit}, \delta_{rud} = \delta_{rud_{max}})} = \frac{S_{VAFC} C_{Y_{AFC}}(\beta = \beta_{crit}, \delta_{rud} = \delta_{rud_{max}})}{S_{VNoAFC} C_{Y_{NoAFC}}(\beta = \beta_{crit}, \delta_{rud} = \delta_{rud_{max}})} = 1$$

Equation 1

Rearranging this establishes the relationship between non-dimensional aerodynamic performance and the amount by which the vertical tail can be downsized, as shown in Equation 2. This demonstrates that the change in vertical tail area is directly proportional to the change in net side-force capability of the vertical tail and rudder over a critical sideslip angle. This equation is used to determine the extent to which a vertical tail can be down-sized with the application of AFC. Sub-scale test data indicate that AFC is capable of producing the effects required to provide the 17% tail size reduction assumed in this study.

$$\frac{S_{VAFC}}{S_{VNoAFC}} = \frac{C_{Y_{NoAFC}}(\beta = \beta_{crit}, \delta_{rud} = \delta_{rud_{max}})}{C_{Y_{AFC}}(\beta = \beta_{crit}, \delta_{rud} = \delta_{rud_{max}})}$$

Equation 2

4. Operations of an AFC Vertical Tail in a Flight Environment

To define an AFC system, the operating conditions and functional requirements must be established. Below, the environment in which the AFC System is required to operate and perform is discussed and system functional requirements are established. From the functional requirements, assumed AFC systems are developed so that the AFC system properties and NPV evaluations can be performed.

4.1. Operating Conditions and Environments

The flight envelope over which AFC is critical is limited to a constrained altitude and speed range. The primary design conditions for the AFC-enabled rudder and vertical tail have been shown to be engine-out conditions. The yawing moment coefficient (yawing moment divided by dynamic pressure and wing span) associated with a failed engine decreases with increasing airspeed. This is because thrust and therefore dimensional yawing moment decreases with increasing speed (due to

the natural lapse characteristics of turbofan engines) and the dynamic pressure increase. A notional illustration of the yawing moment coefficient capability of a rudder as compared to the yawing moment coefficient generated by an engine failure is provided in Figure 7. At sufficiently high airspeeds, full rudder capability of a reduced tail-size configuration will have sufficient control margin as compared to the engine-out yawing moment and the AFC system will not be needed. Determining the exact speed range over which AFC is critical is beyond the scope of the study, but it is expected to be limited to low speeds associated with takeoff, approach, and landing phases of flight, as shown by the shading and annotations in Figure 7. A similar effect is observed with the engine thrust lapse with altitude. As the airplane climbs, there is also an altitude above which the AFC system will not be needed.

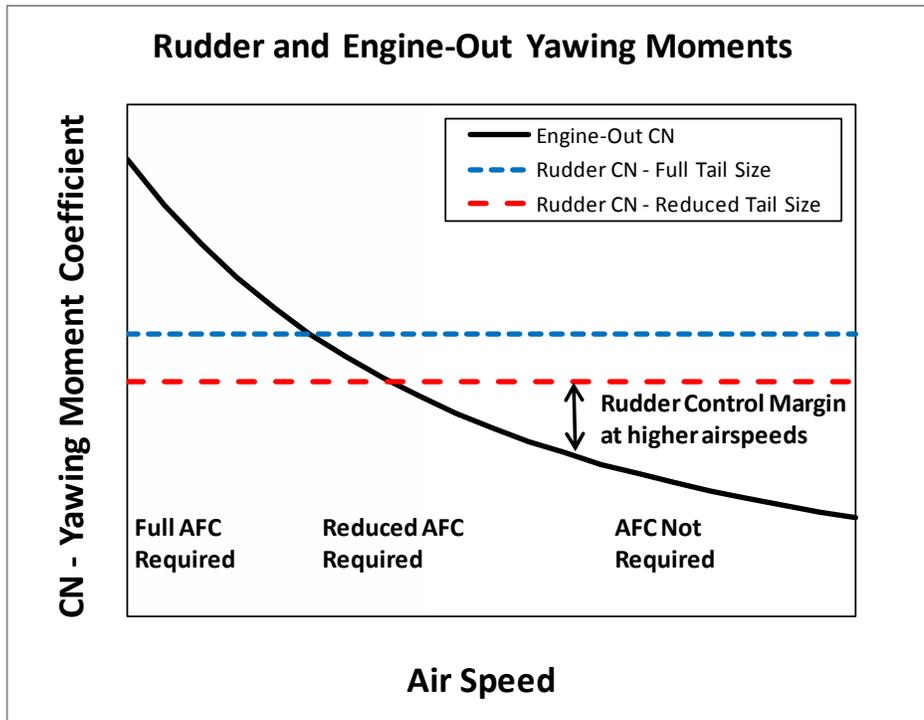


Figure 7: Notional Yawing Moment Coefficients for Full Rudder and Engine-out Thrust Asymmetries.

The system must operate in all environmental conditions expected for takeoff, climb, approach, and landing. This includes the full range of atmospheric conditions expected at these conditions. The full ranges of expected temperature and moisture content need to be considered when designing the AFC system.

4.2. Functional Requirements

In order to develop an assumed AFC system, functional requirements are established based on the performance requirements of the system, the environment in which it must operate, allowable failure rates, and maintenance considerations.

4.2.1. Requirements for System Operation

AFC is assumed to provide the required aerodynamic benefit primarily by delaying the onset of flow separation. For dynamic engine failures, where a large yawing moment develops rapidly, the rudder is commanded to full deflection over a short period of time. In such a situation, the AFC system is required to prevent flow separation. This requires that the AFC system be operational and effective prior to the rudder reaching a deflection at which flow separation is expected to occur.

Both versions of AFC actuators considered for the study are deemed to be excessively noisy for routine operation. The AFC system is required to be minimally-impacting to ramp, community, and interior noise production. Since the primary design condition for the AFC system is an emergency situation, increased noise production is acceptable when the AFC system is required to be effective. Any in-service systems tests needed to provide acceptable availability are required to be performed in a low-noise way.

4.2.2. AFC System Availability Requirements

The availability of the system is required to satisfy the regulations in FARs 25.671(c) and 25.1309(b), which state:

FAR 25.671(c): The airplane must be shown by analysis, tests, or both, to be capable of continued safe flight and landing after any of the following failures or jamming in the flight control system and surfaces (including trim, lift, drag, and feel systems), within the normal flight envelope, without requiring exceptional piloting skill or strength. Probable malfunctions must have only minor effects on control system operation and must be capable of being readily counteracted by the pilot.

1. Any single failure, excluding jamming (for example, disconnection or failure of mechanical elements, or structural failure of hydraulic components, such as actuators, control spool housing, and valves).
2. Any combination of failures not shown to be extremely improbable, excluding jamming (for example, dual electrical or hydraulic system failures, or any single failure in combination with any probable hydraulic or electrical failure).

FAR 25.1309(b): The airplane systems and associated components, considered separately and in relation to other systems, must be designed so that—

1. The occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable, and
2. The occurrence of any other failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions is improbable.

Based on the FARs above and the critical design conditions for the system, the critical scenario is determined to be an engine failure combined with AFC system loss. The probability of these two failures happening in the critical flight phases must be less than 1×10^{-9} . Using the limited exposure times of the critical flight phases, discussed in Section 4.1, and typical engine failure rates, it is determined that the AFC system failure rate should be on the order of 5×10^{-4} per flight hour or better.

4.2.3. Environmental Performance Requirements

The AFC system is required to provide the aerodynamic benefit in all environmental conditions expected for the takeoff, climb, approach, and landing flight phases. Accounting for the large range of potential temperature and moisture contents and recognizing the fact that the AFC actuators provide their benefit by moving air through an orifice leads to the assumption that ice protection for the AFC actuators is required. Furthermore, each actuator orifice is required to be self-clearing with respect to bugs and/or debris within the time from activation to effectiveness, and is also required to have adequate drainage to prevent build-up of water.

4.2.4. System Monitoring and Testing Requirements

To support the AFC system availability requirements, the impact of latent failures on system availability must be minimized. Accordingly, the AFC system requires means to test the system functionality, including at the component level, sufficiently close to the time period of potential system need. System monitoring also allows potential hazards to be mitigated through operational adjustments and dispatch to be permitted with a degraded systems.

4.2.5. Structural Heating Limitations

Both AFC systems have the potential to be using significant amounts of power, which has the potential to produce heat emissions. This concern is most relevant to the sweep jet systems, where high-pressure air is required to power the actuators. Such air sources have the potential to be high-temperature sources. The AFC systems are not allowed to heat the aircraft structure (external surfaces or internal components) to unacceptably high levels.

4.2.6. Installation, Maintenance, and Overhaul

It is crucial that the vertical stabilizer and AFC system are designed with ease of installation and maintenance in mind. A significant installation time for the AFC system will create a longer production time for each airplane, decreasing production rates. Since the longest airplane in the family will not have the AFC system installed, significant system installation times could create inconsistencies and bottle necks in the production process. Significant removal and replacement times for the system would also be onerous for maintenance considerations.

To ensure acceptable installation, maintenance, and overhaul times, the AFC system should be designed in a modular fashion. To minimize spares that the airlines would need to have available, the actuators should be reasonably interchangeable along the span. For system optimization, it is recognized that some degree of span-wise actuator variation may be needed. For the purposes of this system integration study it is assumed that three or fewer actuator sizes are used along the span. It is also assumed that all operational requirements can be met with a small number of failed actuators, thereby minimizing the impact on dispatch reliability and/or crew procedures in such situations.

5. AFC System Design

To be able to evaluate both AFC technologies on equal footing, common AFC System design is leveraged to the greatest extent possible. The assumed system designs deviate only when the unique power sources for the actuators require that the designs be different.

5.1. Spatial Integration

One of the objectives of initial layout work was to determine whether the existing tail structural and systems architecture could accommodate the incorporation of the actuators in the region behind the rear spar and ahead of the rudder, or whether changes such as moving the rear spar forward would be required. This volume, which is largely open with the exception of the area that contains the rudder actuators, is broken up by ribs. Both actuation technologies target this volume for installation of the AFC actuators.

An example of how these actuators could be integrated, laying flat relative to the skin of the vertical tail, is provide in Figure 8 for synthetic jet actuators. The sweep jet actuators would be integrated into the volume of the vertical tail in a similar fashion. The approach illustrated in Figure 8 assumes that the actuators fit in a single row along the span. This assumption is not always valid, depending on the actuator size required. Sketches for alternate layouts are presented in Figure 9, which shows actuators laying flat relative to the skin in one or two rows, in addition to a vertically-stacked configuration. The options available would depend on the critical linear dimension for the actuator, the required orientation, and the volume of the actuator.

Based on the layout work, it was determined while challenges exist, particularly in the trailing edge bays where the rudder actuators reside, that no such major modifications were required. Had such changes been required, their impact on cost, and weight would have needed to have been evaluated.

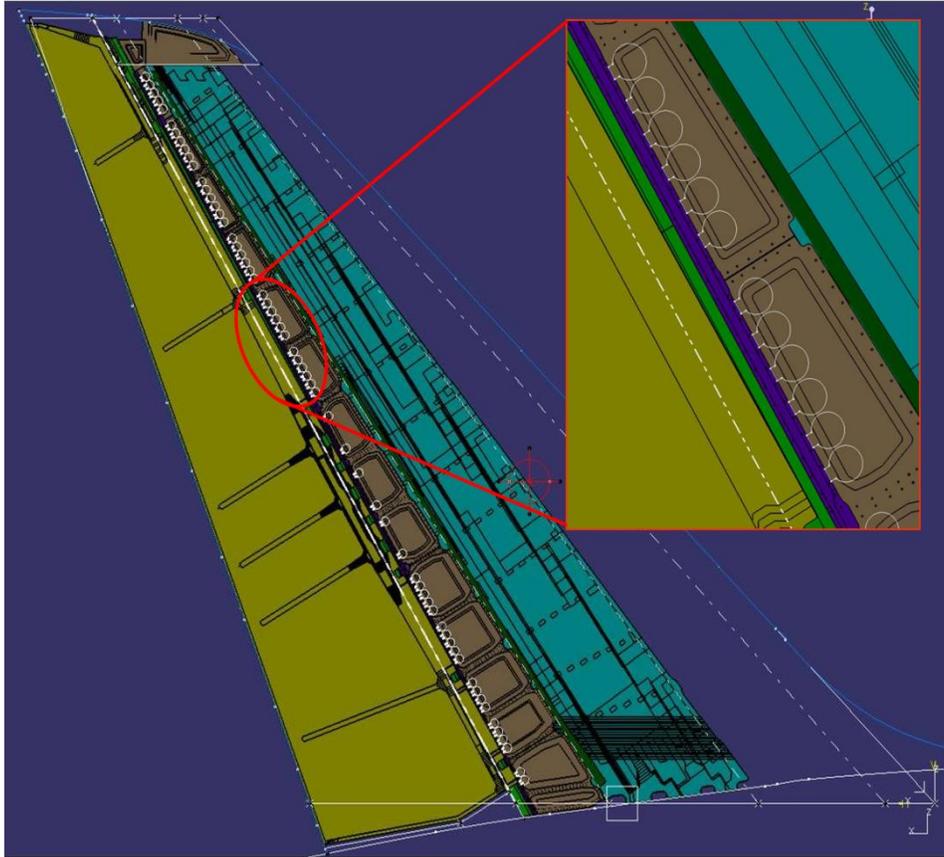


Figure 8: Synthetic Jet Integration

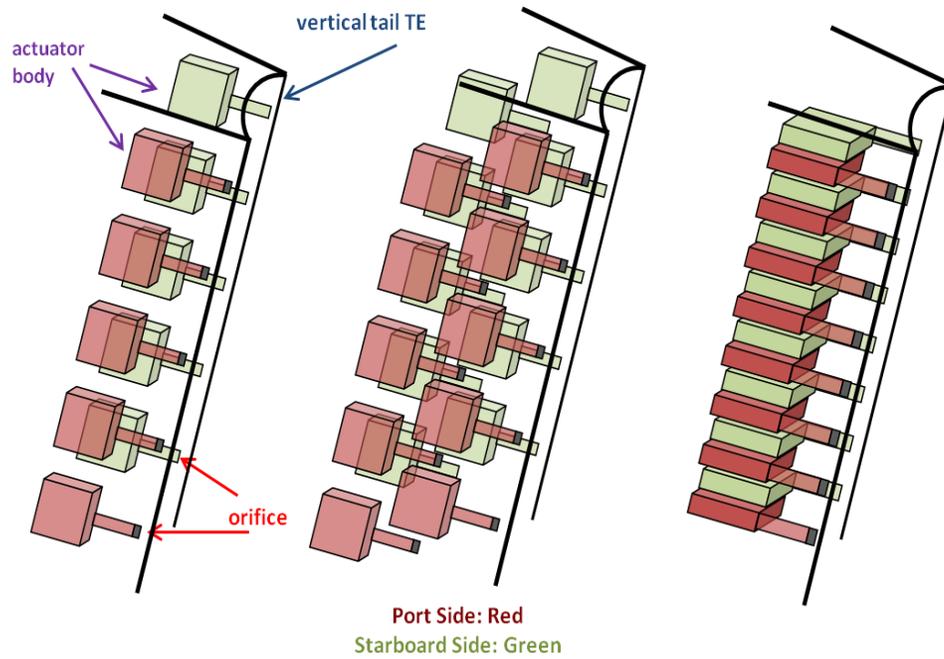


Figure 9: Alternate AFC Actuator Layouts

5.2. Synthetic Jet and Sweep Jet System Operation

Given the potentially excessive noise that the actuators might create, both the synthetic jet and sweep jet AFC systems are required to be operational only when the flight condition is consistent with the need for AFC and the rudder deflection is sufficient to produce flow separation. Accordingly, the following AFC arm and activation scheme is proposed:

- Arming:
 - The system shall be armed based on airspeed, when the airspeed is in the range deemed critical for AFC operation
- Activation:
 - The system shall be activated based on arm state and rudder deflection. The system will activate if:
 - The system is armed
AND
 - The rudder is at a deflection that could allow it to reach an AFC-critical deflection with the rudder moving at full rate

For the purposes of this study, it is assumed that both actuators are effective within 200 ms after the activation command. This assumption is validated for the synthetic jet actuators based on the fact that the actuators become effective in time periods on the order of one actuation period and the high actuation frequencies of the piezoelectric disks, discussed in Reference (2). Thus, it can be assumed that the actuator is effective within 50 ms of applying power. A similar response time can be assumed for the response of the sweep jet actuators based on input from sweep jet technology experts, Reference (7). With 50 ms consumed by the actuators becoming effective after power is applied, the remaining 150 ms provides time for sensing the need for AFC activation, providing the command, and having the other system components respond.

The AFC activation rudder deflection is based on the rudder deflection at which AFC is required (separation deflection), as well as the maximum rudder deflection rate and the time required for the AFC actuators to become effective:

$$\delta_{r_{activation}} = \delta_{r_{AFC\ Req'd}} - \dot{\delta}_{r_{max}} * (t_{AFC\ effective} - t_{AFC\ activation})$$

Equation 3

Since flow separation is associated with large rudder deflections and the delay time is short, reasonable activation thresholds are possible even with high rudder rate capabilities that are typical for primary flight control surfaces. This fact allows the chosen activation scheme to support the requirement to be non-impacting to community and interior noise, as the system will not activate with normal rudder usage.

Figure 10 shows the varying regions, where AFC is always off, always on, and transitioning to full power.

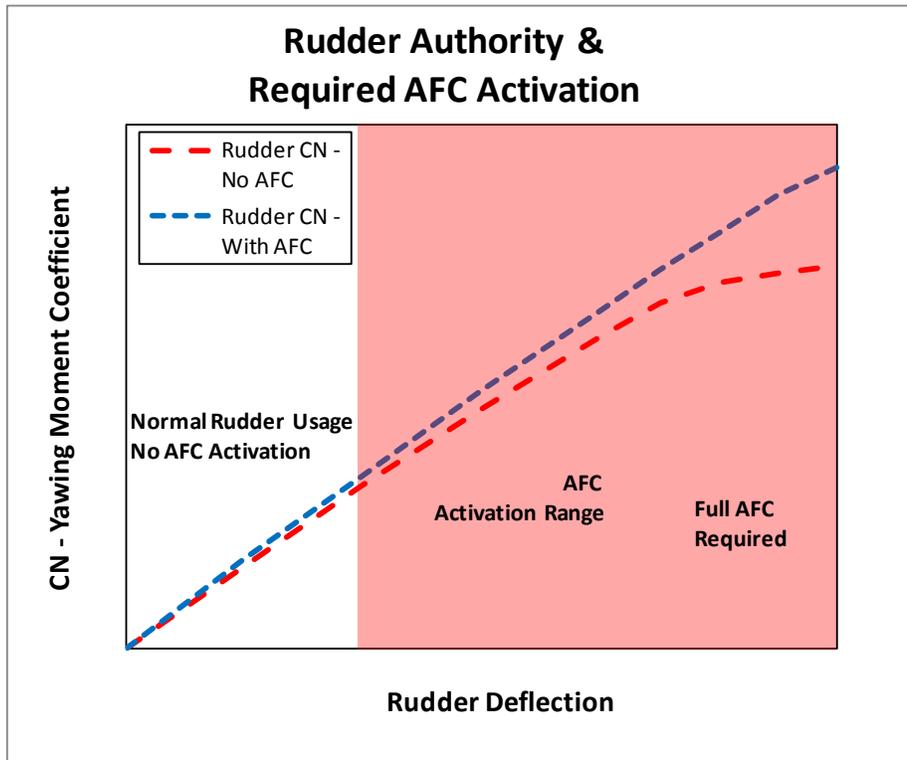


Figure 10: Illustration of AFC Activation Using Rudder Deflection.

The AFC system will only be activated on the suction side of the stabilizer, as there is no aerodynamic benefit to activating AFC on the pressure side. Determination of the pressure and suction side can be determined based on the direction of rudder deflection, as shown in Figure 11. Activating one side at a time will minimize the power that both the synthetic and sweep jet actuators will consume from their respective power sources.

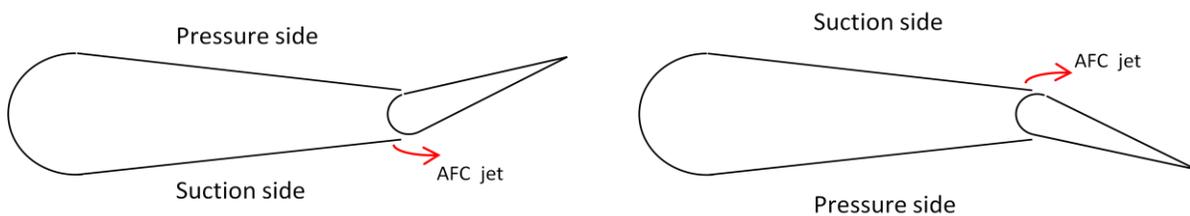


Figure 11: Illustration of Pressure and Suction Sides of Vertical Tail and Rudder

5.3. Flight Control System Architecture

The flight control system is architected to ensure that the AFC system failure rate is on the order of 5×10^{-4} , that the required arm and activation logic is supported, and that the remainder of the functional requirements are supported by the system. System function is dependent on actuator availability, electrical and/or pneumatic power availability, in addition to availability of the logic based control.

It is assumed that the baseline flight control architecture has sufficient redundancy in the flight control modules (FCMs) to achieve availability requirements. The FCMs receive the required data to support AFC system arming, activation, and testing and provide the commands to control the system.

The AFC system is proposed to use electronic line replaceable units (LRUs) for AFC actuator command, control, and testing. A dual LRU system is employed to reduce the rates of full system failure. Each LRU will be capable of transmitting to the FCMs the system and actuator states for arming, testing, and activation, as well as anti-ice heat state, and fault indication.

Each actuator will have an integral sensor for determining actuator health status. Given the differences in actuator technology, this sensor could differ between the two actuator types.

Although both technologies could be powered from other airplane systems such as the engines and their generators, the Auxiliary Power Unit (APU) was targeted as it is not typically used during takeoff and landing and all available power could be used. With the potential for the AFC system to require significant amounts of power, this allows the study to be less impacted by power constraints. It is assumed that the APU could be designed to provide either the required electric or pneumatic power. Depending on the airplane design, examples can be found where APUs support either possibility. This approach requires that the APU remain powered up through takeoff. Once the plane has surpassed speeds at which AFC would be needed, it could then be powered off for the remainder of climb and cruise. The APU would then need to be started prior to final approach.

Using this architecture, an assessment of the AFC system failure rate was performed. It was found to support the requirements discussed in Section 4.2.2. The primary contributor to the system failure rate is the APU, which is a single-threaded power source.

A concern specific to landing performance is the relatively poor in-flight start reliability of APUs, which is on the order of 99.5%. In cases where the APU fails to start, the approach configuration and landing speeds would require adjustment. On missions that are landing field-length limited, such adjustments could result in the need to land at an alternate airport. Applying AFC to a mid-size long range airplane minimizes the potential impact, as very few missions are expected to be landing-field length limited. Since this concern is mission-specific, it has the potential to be mitigated by leaving the APU on for the entire mission in situations that are landing field length limited.

5.4. Power Distribution

Given that the two types of actuators use significantly different power sources, differing power distribution methods are required. The synthetic jet system will use an electrical system to condition and distribute electrical power. The sweep jet system will use a pneumatic system to condition and distribute the high-pressure air.

5.4.1. Synthetic Jet Power Distribution

Each synthetic jet LRU is provided independent 235 VAC 3-phase electrical power from an APU generator for the purposes of powering the synthetic jet actuators. Each LRU is powered by the ship systems to ensure that the LRU is functional and capable of providing anti-ice protection without the APU running. Each LRU includes a transformer/rectifier unit (TRU) as well as a signal generator to shape the TRU output as needed for the actuators (such as a sine wave or duty cycle modification for the synthetic jets). Each LRU shall be powered “ON” during all normal operations as it also controls de-icing heat to its actuators. The LRUs must also include high-integrity switching functions to correctly activate actuators on the suction side of the stabilizer (see Figure 11), as well as to switch from actuator de-icing heat to actuator power.

The proposed synthetic jet architecture is illustrated in Figure 12. The figure uses a notional 60 AFC actuators. The exact number of actuators required will be a balance of aerodynamic performance and system complexity, including the ability to integrate the actuators into the vertical tail. This is discussed in more detail in Section 6.1.

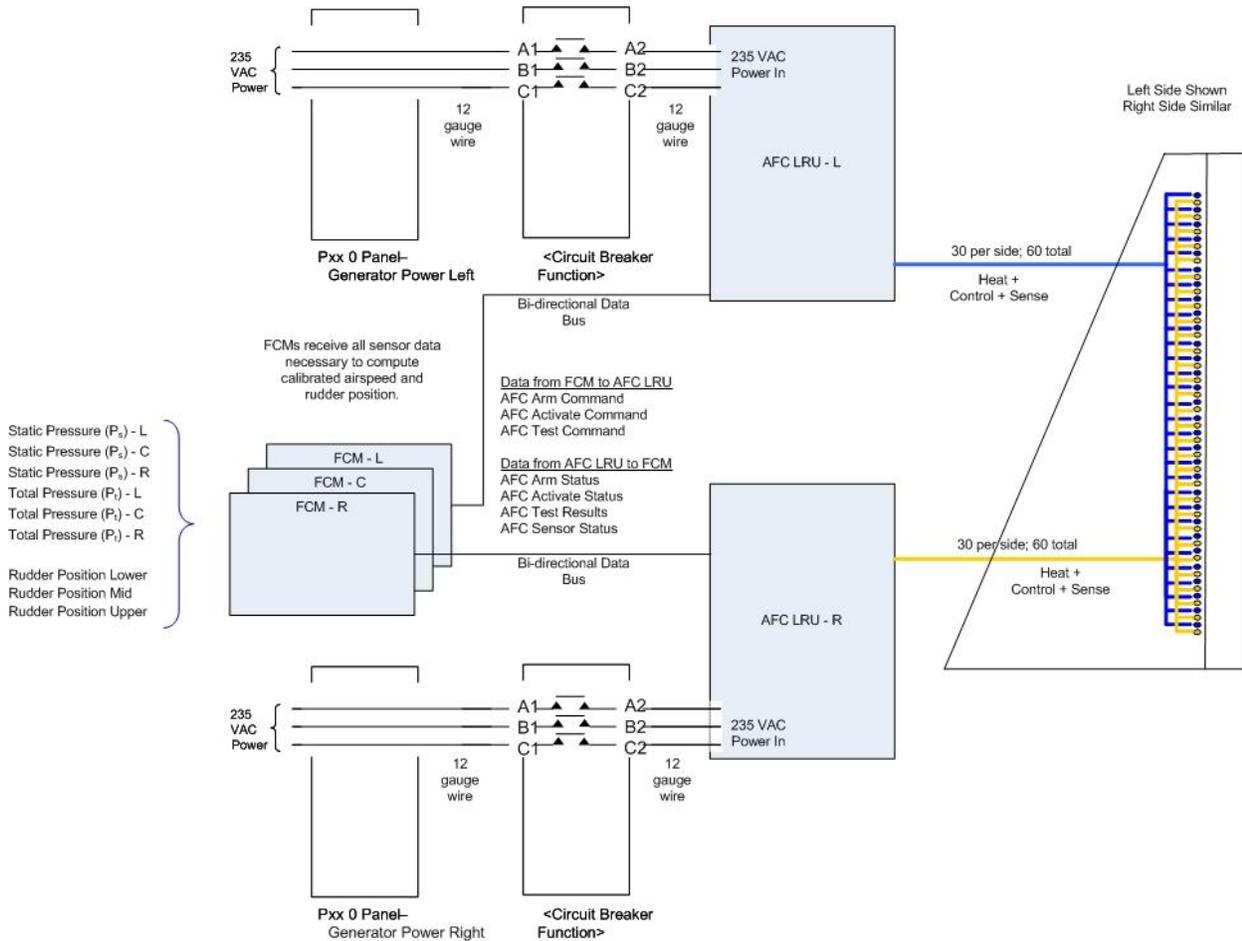


Figure 12: Proposed Synthetic Jet Control System Architecture

5.4.2. Sweep Jet Power Distribution

The sweep jet system will use the compressed air from the APU to power the AFC actuators. The high-pressure air is distributed through ducting that is routed from the APU to the AFC actuators. The flow is controlled by a series of control valves. Each LRU is powered by the ship systems to ensure that the LRU is functional and capable of positioning control valves and providing anti-ice protection without the APU running.

A shut-off valve isolates the APU and AFC system from the remainder of the pneumatic system to ensure all of the available APU flow is provided to the AFC actuators. To ensure that the actuators respond quickly enough to develop effectiveness, it is assumed that the trunk-line must be pre-pressurized when the system is in the armed state and control valves at each individual actuator will be commanded open when the system is activated. Shut-off valves to prevent flow to the AFC trunk-line in times when the system is not armed are also assumed and controlled by the AFC LRUs.

Pressurized air from the APU is known to be a high-temperature air source, with temperatures in the range of 400 °F, well above the allowable temperatures for internal structure and the rudder and fin surface. It is assumed that a combination of insulation for the ducting and a pre-cooler to cool the air from the APU and prevent excessive heating to the critical structural elements.

The proposed control architecture for the sweep jet system is analogous to the architecture for the synthetic jet system, illustrated in Figure 12, with the FCMs interacting with the LRUs in the same fashion, but the LRUs controlling pneumatic valves to provide power to the sweep jet actuators. A schematic of the power distribution architecture is presented in Figure 13.

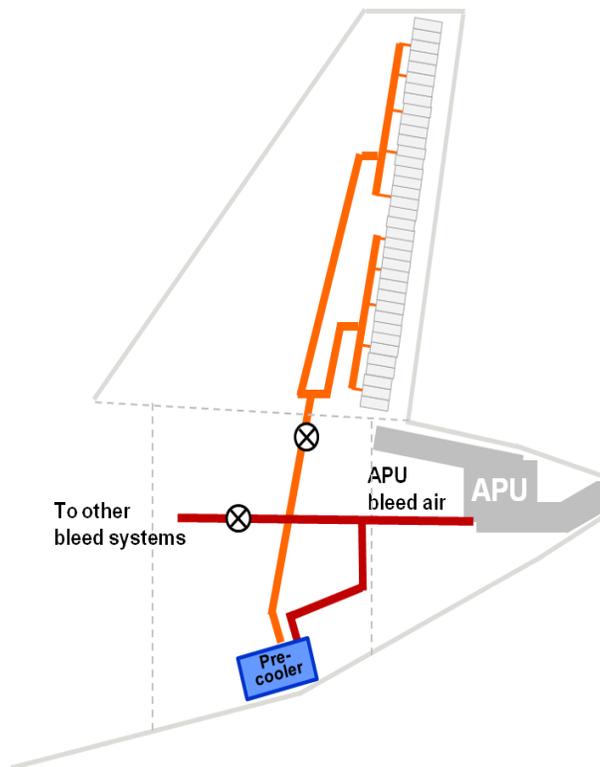


Figure 13: Sweep Jet Power Distribution

5.5. Functional Testing

Testing of the AFC system will work through the LRUs, which will have the capability of monitoring the health of internal components, external interfaces (power, data bus, etc.), and actuator health. Each AFC actuator type will have sensors that will enable health monitoring. Due to noise constraints, actuator test functions will not be allowed to activate all actuators simultaneously at full power for either synthetic jet or sweep jet systems.

Automated tests will run prior to takeoff and approach in order to limit the exposure time of AFC system failures. Actions taken in response to system degradations will depend on when it is detected and the amount of AFC effectiveness lost. Having a limited number of spaced-out actuators inoperative is expected to be permissible and not result in any immediate maintenance action or operational impact.

The precise maintenance and dispatch capability would need to consider the level of AFC effectiveness lost, the probabilities associated with subsequent failures from a degraded AFC state, and the hazards of the subsequent failures. It would also need to consider the operational adjustments and their impact to mission performance. Developing a detailed maintenance and dispatch schedule is beyond the scope of this study.

6. AFC System Properties

In order to validate that the AFC system can be integrated into the study airplane, trade studies were performed to understand the power required to support the AFC system, the space required to integrate the system into the vertical tail, and to quantify the weights of the system. System characteristics are compared against known constraints to understand if a given AFC system configuration is thought to be viable, from an integration perspective. The constraints are different for the two candidate AFC systems and they are discussed in Sections 6.1.1 and 0 below. The resultant weights are key components in performing the NPV evaluation, which is discussed in Section 7.

This study assumes both power consumption and weight scale with size – power is proportional to the area of the actuator orifice and weight scales linearly with volume. It is expected that power and weight do not necessarily to scale linearly, but not enough data is available to include a better estimation. Thus, the scaling used below for both sweep and synthetic jets is expected to be conservative, and therefore can be considered a worst case scenario.

The trade study performed is driven by three key AFC system performance and design parameters – the number of actuators, the level of momentum addition that the system provides, and the velocity of the jet. These input parameters are used to estimate required actuator sizes, power required (electrical or pneumatic), and the characteristics of the system for routing the power.

The momentum levels are characterized by the non-dimensional momentum coefficient, provided in Equation 4 and the velocity is characterized by the non-dimensional blowing ratio, provided in Equation 5. The parameter n in Equation 4 represents the number of AFC actuators. These three parameters are used to define the design space over which AFC systems are analyzed. Sea-level standard day densities are assumed for both the jet and free-stream densities. A nominal low-speed design condition of 130 knots is used to define the free-stream velocity. The area of the vertical tail is defined to be 470 ft² for the study airplane.

$$C_{\mu} = \frac{2\rho_j n A_e U_j^2}{\rho_{\infty} U_{\infty}^2 S_v}$$

Equation 4

$$C_b = \frac{U_j}{U_{\infty}}$$

Equation 5

where the variables in the above equations are defined as

| | |
|-----------------|----------------------------|
| ρ_j | Density of actuator jet |
| N | Number of jets |
| A_e | Exit area of jet orifice |
| U_j | Time averaged jet velocity |
| ρ_{∞} | Free stream density |
| U_{∞} | Free stream velocity |
| S_v | Area of vertical tail |

The amount of C_{μ} needed to create the necessary increase in side force and yawing moment is a heavily debated topic. Testing using AFC at flight-scale Reynolds numbers has not yet been completed, so scaling effects from small-scale wind tunnel Reynolds numbers to full scale Reynolds numbers are not yet understood. Estimates for the C_{μ} required to support the 17% vertical tail size reduction vary widely, but is expected to be comparable for both technologies. An optimistic estimate of the required C_{μ} is 0.5% and a pessimistic estimate using a steady-blowing analogy is 5%. The range used for the trade studies is 0.5% to 2.5%. Going all the way to 5% resulted in grossly excessive power requirements and this estimate is thought to be overly pessimistic given that the oscillating nature of the actuation techniques is more efficient than steady-blowing.

The appropriate range of C_b and n is actuator specific and is discussed in Section 6.1 and Section 6.2.

6.1. Synthetic Jet AFC System Trade Study

The design space used for the synthetic jet AFC system trade study uses the ranges provided below, in Table 1. The lower limit for the blowing ratio is set based on experimental data indicating that AFC effectiveness drops off significantly when the jet velocity falls too far below the free-stream velocity. The upper limit is set to prevent the peak Mach numbers in the jet from approaching sonic conditions – this is a known limitation for synthetic jets. The range used for the number of actuators was established to ensure that a reasonable size actuator is utilized, without resulting in an impractical number of actuators being used along the span. It should be noted that the efficacy of an actuator configuration may be dependent on the spacing between actuators, not just the overall C_{μ} . This potential impact is not explored here, but the impact of such spacing differences on the system integration can be gleaned from the charts that follow. The parameter D , in this table represents any duty-cycle applied to the AFC actuators for power reduction purposes.

According to technology experts, synthetic jet duty cycle can be reduced to levels as low as 20% through pulse width modulation and still have an appreciable effect, Reference (8). This would be advantageous to overall system design due to the impact it would have on power requirements.

Though a 20% duty cycle is likely lower than what would be required for full scale needs, further study should be done into this field as it could considerably reduce power consumption by the AFC system. The low range was set based on the preliminary research and the expectation that the full-scale actuator would not be able to take full advantage. The upper limit was set to take no duty-cycle credit.

| Input | Low Value | High Value |
|---------|-----------|------------|
| C_μ | 0.5% | 2.5% |
| C_b | 1 | 4 |
| n | 50 | 200 |
| D | 40% | 100% |

Table 1: Synthetic Jet Design Space Input Variables

Equation 6 establishes the relationship between the peak jet velocity and the average jet velocity and allows the peak jet Mach number to be identified using the free-stream speed of sound.

$$U_j = \frac{2U_{j,peak}\pi}{3}$$

Equation 6

The defined momentum coefficient and blowing ratio can be used to determine the required exit area for the jet by rearranging Equation 4, substituting using Equation 5, and assuming standard temperature and pressure for the jet:

$$A_e = \frac{C_\mu S_v}{2 \cdot 100 \cdot n C_b^2}$$

Equation 7

Current actuator designs are then used to define the actuator geometry (width, volume, etc.) by scaling the exit area based on input from synthetic jet technology experts, Reference (8).

The fluidic power generated by the jets is defined by Equation 8. This is converted into the required electrical power based on an electric-to-fluidic power conversion factor and a duty-cycle factor, as shown in Equation 9. Based on sub-scale experiments the electric-to-fluidic power conversion is assumed to be 40%, Reference (8). Duty cycle is varied according to Table 1.

$$W_{fluidic} = \frac{n\rho A_e U_j^3}{2}$$

Equation 8

$$W_{electric} = \frac{DW_{fluidic}}{\eta_a}$$

Equation 9

The weight of the system is determined by establishing the weights of the actuators, the LRUs, and the required wiring. Actuator weights are estimated assuming that 50% of the actuator volume is made up of aluminum, accounting for the fact that the mounting plates of the actuator body have holes the size of the piezoelectric disc bored out. The weight of the piezoelectric disc is neglected for simplicity. The LRUs that handle power conversion and control are estimated to weigh 0.6 lb/kW,

Reference (9). Wire weight is determined based on the gauge required to route the power to each individual actuator and an assumed average wire length. With the assumption that the LRUs are near the tail, the average wire length was estimated to be 1.5 times the span of the vertical tail. After determining the component weights, an additional 10% of weight was added to account for installation hardware.

6.1.1. Synthetic Jet AFC System Design Constraints

The synthetic jet AFC system was evaluated against constraints related to the available power, available space for the actuators. The constraints applied and assumptions behind them are provided below:

- Power required must be less than 450 kW. This limitation is associated with the power available using the full capability of an APU with two electric generators. 450 kW is assumed based on APU capabilities on aircraft similar to the study airplane.
- Jet Mach number must be less than 0.8. This limitation is associated with the capability of synthetic jet actuators. Getting beyond a sonic condition is not possible and a reasonable margin to $M=1.0$ was desired to avoid being overly optimistic about the capability of the actuator.
- Total actuator volume per bay (volume between ribs, skins, and vertical aft spar and rudder hinge line) must be less than 2000 in³. Though the bays near the tip of the tail are the smallest, it was determined that the 1/4 of the volume of the bay at the 1/3 span location is a reasonable constraint to apply. This would allow the AFC actuators to be spatially integrated in the bays that are likely to house the rudder actuators. Assuming that some level of AFC actuator variation is permissible along the span, the actuators could be varied to be smaller near the tip if required.
- Higher actuator volume scenarios will require the actuators to be aligned perpendicular to the skin in a stacked configuration similar to that shown in Figure 8. For these scenarios, a fin depth constraint comes into play. For this reason, the maximum actuator width is also limited to be less than 10 inches. This limit is driven by the available width based on the skin-to-skin dimension at the 1/2 span of the tail and is also consistent with some of the largest synthetic jet AFC actuators currently in development. Using the 1/2 span dimensions leverages the assumption that some level of AFC actuator variation is permissible along the span.

A constraint for limiting the gauge of the wire required to distribute the power to the actuators from the LRUs was considered. Required wire gauge is calculated based on the current being carried from the LRUs to the individual wires as part of the weight estimation. Though a practical limit for maximum wire diameter could be developed, it was found to be unnecessary as the other design constraints keep the required wire at 8 AGW or smaller which was determined to be sufficient for this study.

6.1.2. Synthetic Jet AFC System Properties

Synthetic jet AFC systems were characterized using the assumptions mentioned above over the range of momentum coefficients, blowing ratios, and number of actuators provided in Table 1. The system characteristics that result from a nominal duty-cycle of 70% are compared against the design constraints in Figure 14 to Figure 19. Sensitivities to duty cycle are provided in Appendix 10.1. The

shaded areas indicate areas outside of the design space due to the relevant constraint for the figure. Viable configurations (C_{μ} , C_b , n combinations) are indicated with a solid circle symbol to highlight where other design constraints are limiting the design space. Histograms for all viable AFC configurations are also included to provide insight into the most-likely characteristics. The electrical power and peak jet Mach numbers are assumed to be independent of the number of actuators, where the actuator volume and width are dependent on the number of actuators, thus these plots are provided for the high and low end of n .

Figure 14 shows the APU power limit does not constrain the synthetic jet design space for the largest number of actuators. This was chosen as the illustrative case because of the impact that the number of actuators has on the design space is in detail discussed below. Although the APU power limit has the potential to eliminate higher momentum coefficients and blowing ratios, it is observed that the power limitation has negligible impact on the design space at the assumed nominal duty cycle. This is indicated both by the histogram, which shows that the number of viable configurations falls to zero before the 450 kW limit and by the fact that viable designs (highlighted with black circles) do not approach the limit line.

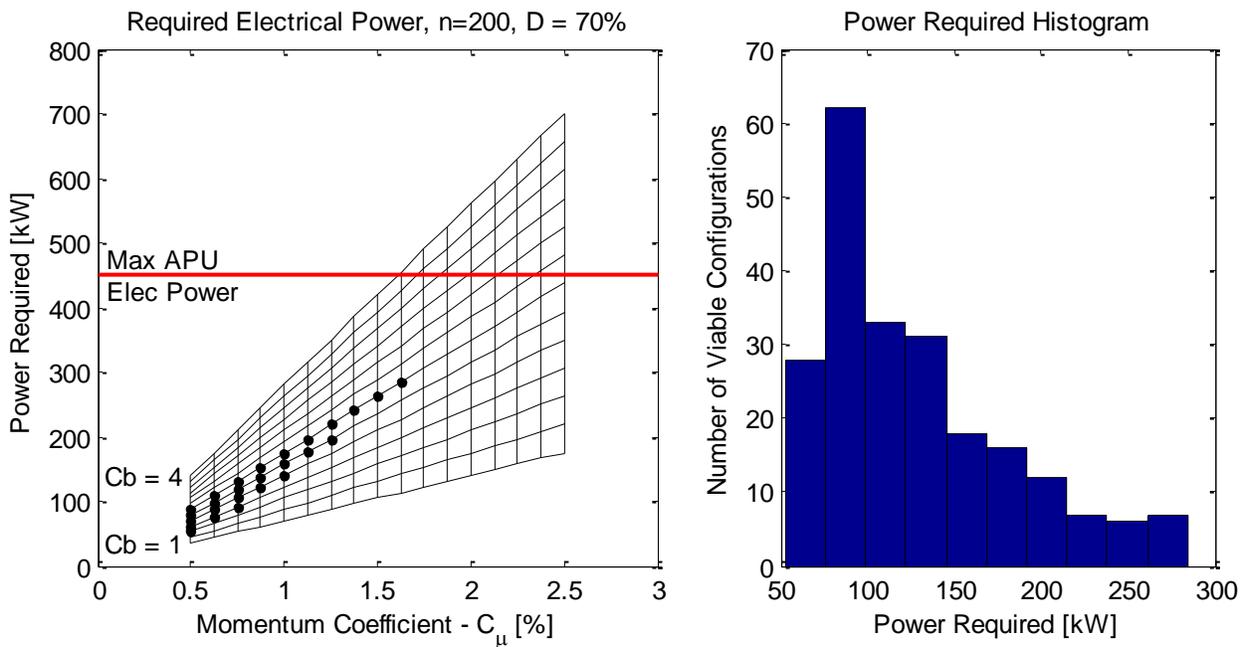


Figure 14: Synthetic Jet AFC System Required Electrical Power ($n = 200$)

Figure 15 shows that the Mach number limitation cuts off all actuator configurations requiring a blowing ratio above approximately 2.5. This expected result indicates that the synthetic jet's inability to produce jet velocities near sonic conditions limits the potential range of viable design configurations.

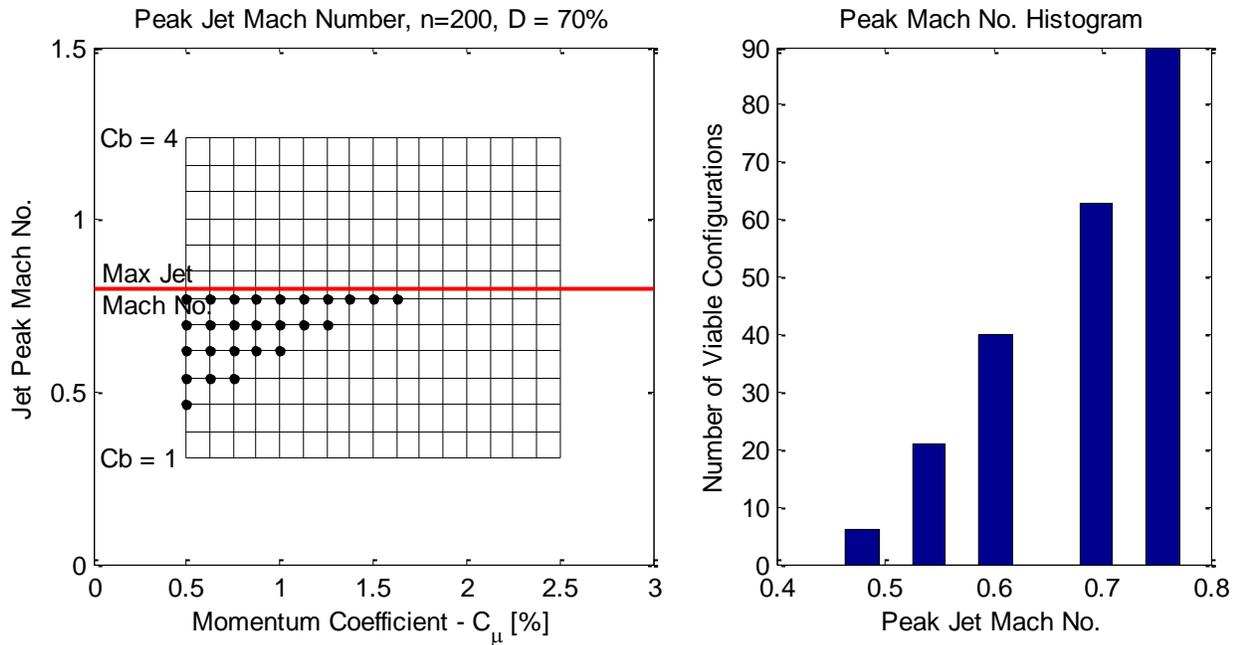


Figure 15: Synthetic Jet AFC System Peak Jet Mach Number ($n = 200$)

Figure 16 to Figure 19 indicate that of the geometric constraints, actuator width is more constraining than the volume occupied by the actuators; this is evident from the histograms indicating that the largest number of viable configurations is nearly coincident with the actuator width limitation. Increasing the number of actuators helps by achieving the same net C_μ with a large number of smaller actuators, keeping the actuator width below the 10 inch constraint. The geometric constraints for the synthetic jet AFC system are the most constraining requirements. Given that the synthetic jet systems tend towards needing a large number of actuators, synthetic jet spatial integration is expected to use the vertical stacking technique shown in Figure 9.

Minimizing the required momentum coefficient is beneficial to system design, lowering both power and spatial requirements. Momentum coefficient is ultimately expected to be set based on full-scale AFC performance capabilities. Though increasing the blowing ratio results in increased power demands, it reduces the impact of spatial constraints, which are identified as the most constraining requirements. For this reason, the AFC system assessed for the NPV trade is assumed to have the highest possible blowing ratio within the limits of the actuator ($C_b = 2.5$). Interrogating the data at a fixed blowing ratio of 2.5 shows that the viable C_μ range is limited to approximately 1.625%; the limiting constraint is the available volume and the actuator width is also very near the limit. The number of actuators used will be a balance of system complexity, weight, and required C_μ . Lower actuator counts will be limited to lower C_μ 's.

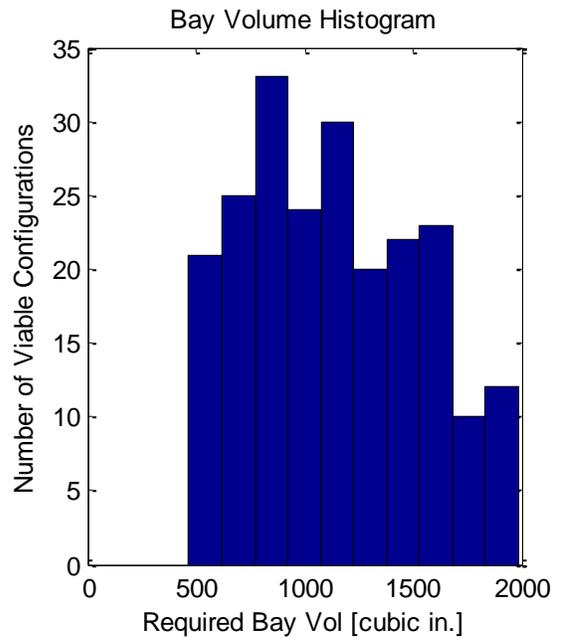
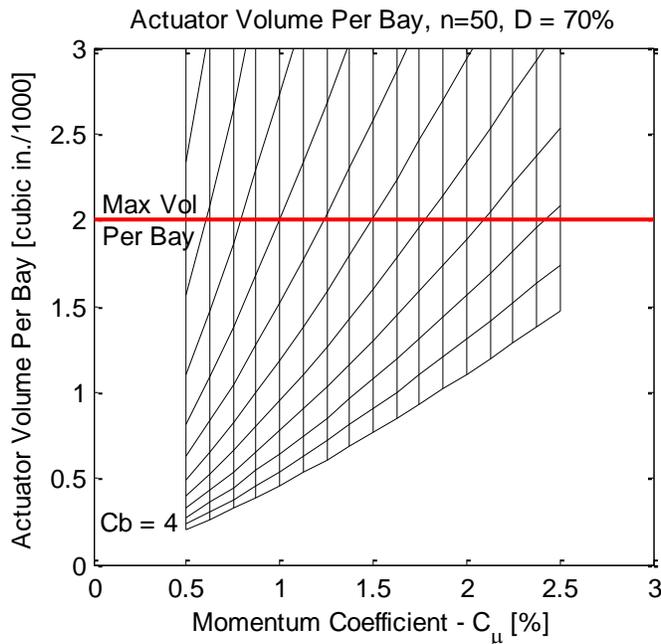


Figure 16: Synthetic Jet AFC System Actuator Volume Per Bay ($n = 50$)

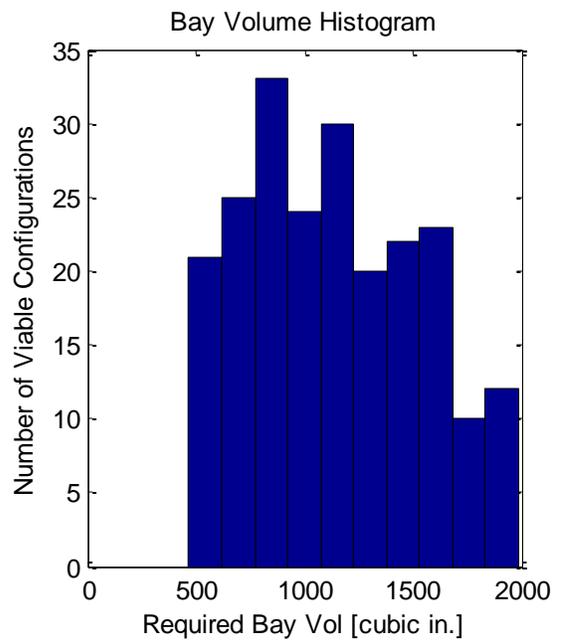
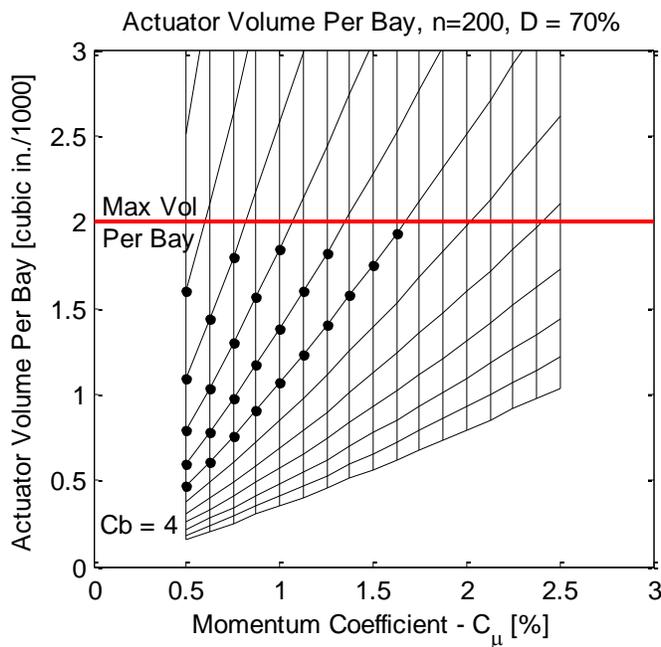


Figure 17: Synthetic Jet AFC System Actuator Volume Per Bay ($n = 200$)

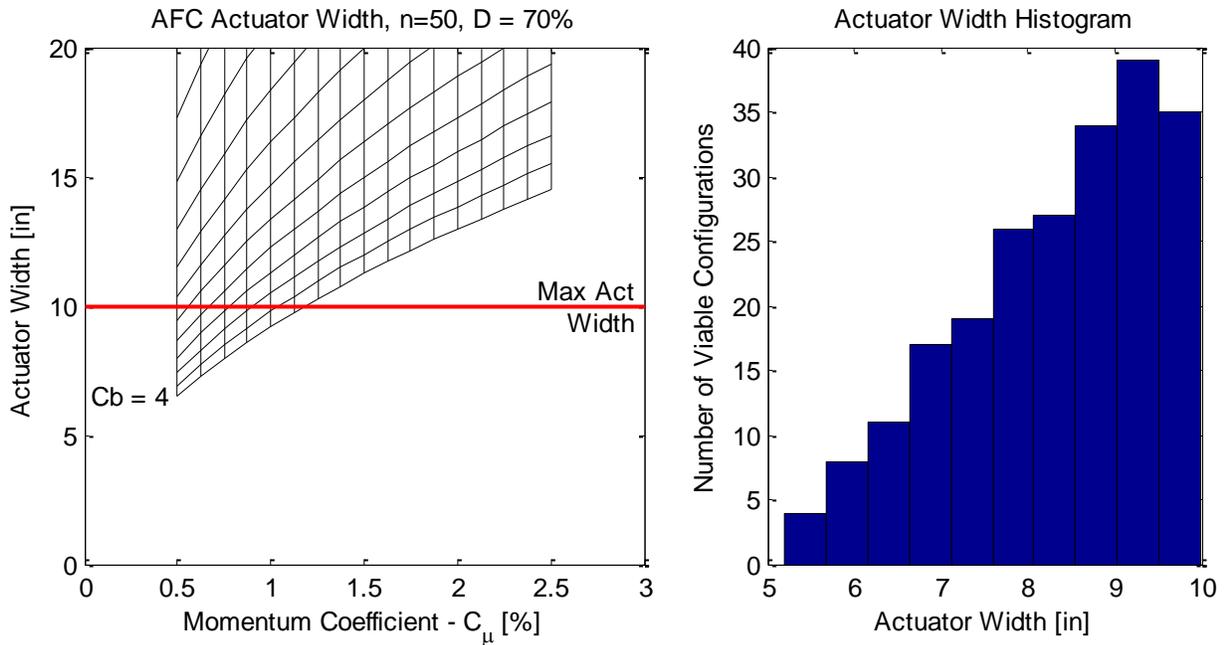


Figure 18: Synthetic Jet AFC System Actuator Width ($n = 50$)

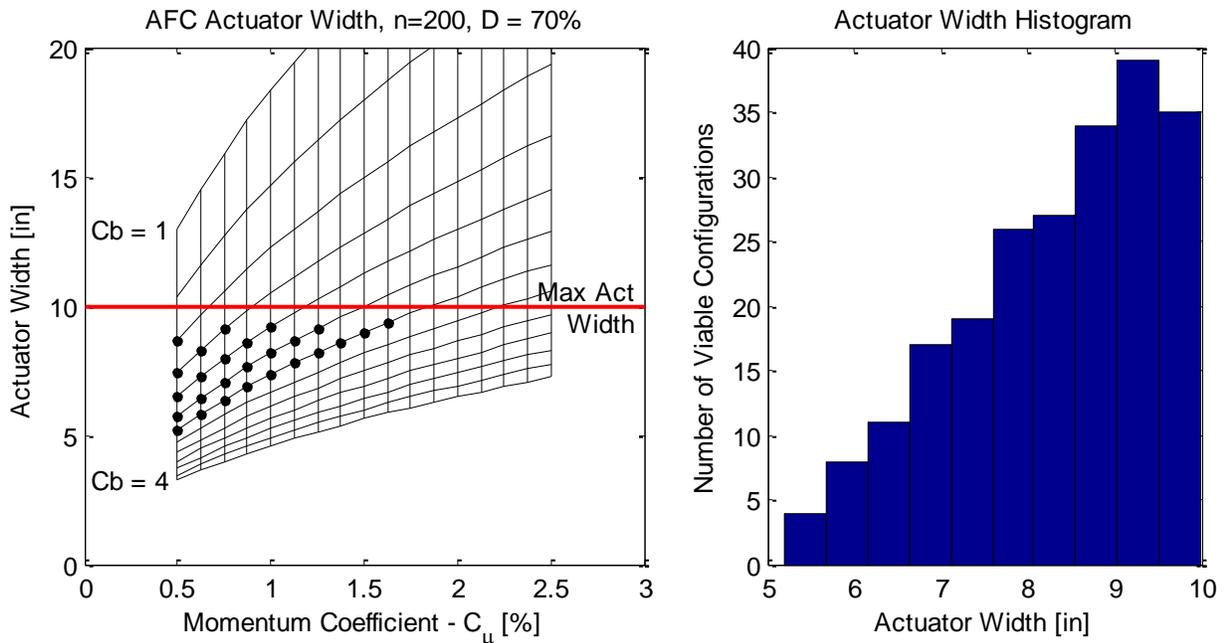


Figure 19: Synthetic Jet AFC System Actuator Width ($n = 200$)

Figure 20 shows weights for the viable configurations with the fixed blowing ratio discussed above ($C_b = 2.5$). For a fixed momentum requirement, overall system weight is relatively insensitive to the number of actuators used. Accordingly, for a given momentum requirement, it is assumed that a lower number of actuators is used to keep part counts as low as possible

The data provided in the Appendix shows that duty-cycle has minimal impact on the overall system weight, the most important parameter used in the NPV tool when characterizing the cost of the system. This result comes from the fact that the actuator weight dominates weight build-up and the

required actuator size does not change with the application of a duty-cycle for power reduction. Accordingly, the system weights can be characterized to range from 550 to 2,250 pounds, depending on the required momentum coefficient. Given that the required momentum is unknown, the range of power requirements is quite dramatic – with a low end of 50 kW and a high-end of 300 kW for a duty cycle of 70%.

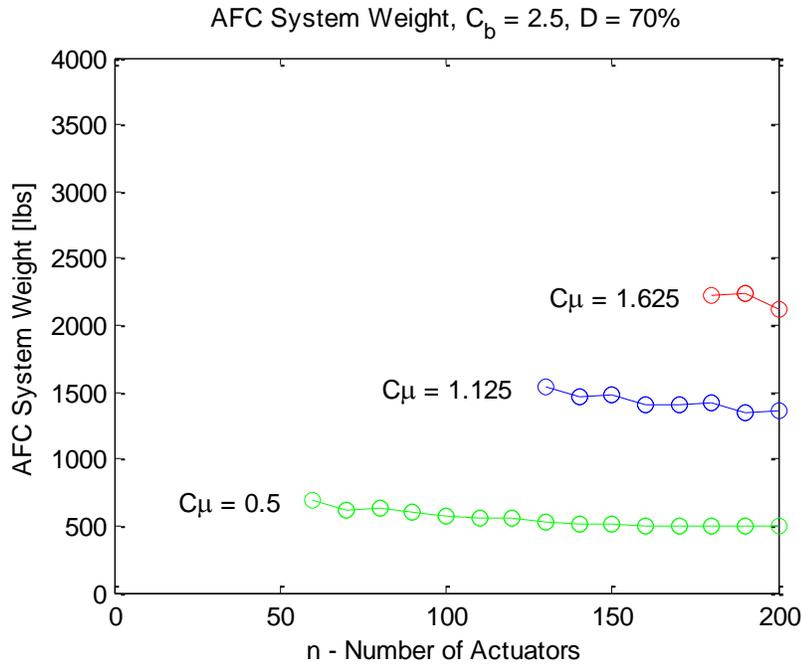


Figure 20: Synthetic Jet AFC System Weight

6.2. Sweep Jet AFC System Trade Study

The range of momentum coefficients explored for the sweep jet AFC system trade study is identical to that which was used for the synthetic jet system. The range of blowing ratios and number of actuators were adjusted based on the performance capabilities of sweep jet actuators. Sweep jets are not limited to sub-sonic jet velocities, thus the design space is opened up, using a range of 3 to 9. This provides the potential to have a dramatically reduced number of actuators, thus the range evaluated for sweep jets is reduced from 10 to 70. While higher jet velocities can result in differences in jet characteristic, potential related changes in performance enhancement are not addressed in this report. The range of trade study input parameters is summarized in Table 2.

| Input | Low Value | High Value |
|-----------|-----------|------------|
| C_{μ} | 0.5% | 2.5% |
| C_b | 3 | 9 |
| n | 10 | 70 |

Table 2: Sweep Jet Design Space Input Variables

As was done with the synthetic jets, the sweep jet AFC system uses Equation 7 to define the actuator exit area. The remainder of the actuator geometry is defined by linearly scaling a representative current actuator design to approximate the over-all size of the actuator.

$$w_e = \sqrt{A_e / AR}$$

Equation 10

The pneumatic power required for the sweep jets is characterized by a mass flow and pressure. The mass flow is characterized using Equation 11.

$$\dot{m} = A_e n U_j \rho_j$$

Equation 11

The pressure required to provide the jet velocity is characterized by a curve fit based on experimental data for a representative actuator geometry provided by NASA and CalTech, Reference (10).

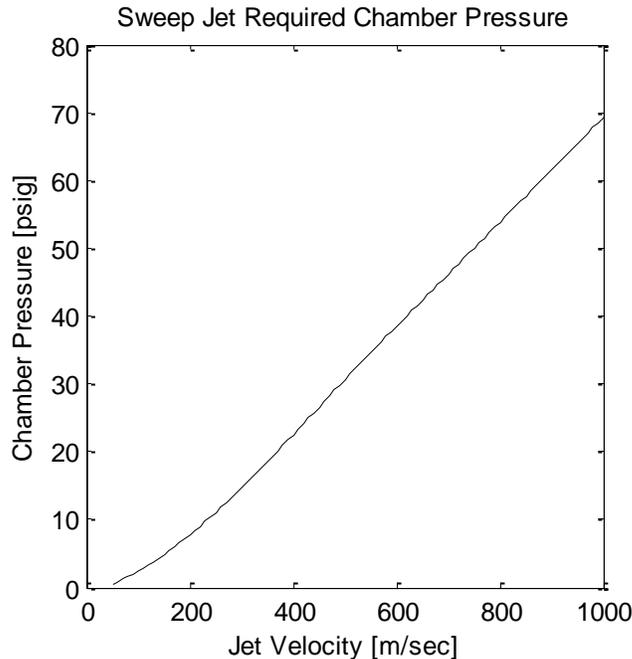


Figure 21: Required Chamber Pressure (PSIG) for Sweep Jet AFC Actuators, Ref (10)

The pneumatic duct work is sized to limit the Mach number within the ducting.

The weight of the system is determined by establishing the weights of the actuators, the LRUs, and the required ducting and valves. Similar to the synthetic jets, the sweep jets actuator weights are estimated assuming that 50% of the actuator volume is made up of aluminum, providing for the cavity to be carved out to make the chamber and channels that set up the sweep jet. The LRUs that command and test the individual AFC control valves are estimated to weigh 20 lbs a piece. The isolation valves are estimated to be 10 lbs each and the individual control valves for each actuator are estimated to be 1 lb a piece. Duct weight is estimated based on the required duct size of the main trunk line – it is assumed that 2.5 times the span of the tail in duct length is required and that smaller

distribution lines from the trunk are covered by this estimate. After determining the component weights, an additional 10% of weight was added to account for installation hardware.

6.2.1. Sweep Jet AFC System Design Constraints

The sweep jet AFC system was evaluated against constraints related to the available pneumatic power, pneumatic distribution, and available space for the actuators. The constraints applied and assumptions behind them are provided below:

- Required mass flow must be below 7.0 lb/sec. This limitation is associated with the mass flow available using the full capability of an APU on aircraft similar to the study airplane.
- Required air pressure at the AFC actuators must be below 30 psig. This limitation is associated with the pressure capability of an APU on aircraft similar to the study airplane, accounting for pressure losses through the pre-cooler.
- Required duct diameter must be below 6.5 inches. This limitation is associated with interfacing the AFC ducting with the typical APU duct diameter (7 inches). The AFC ducting should be one standard duct size below the APU duct, or smaller.
- Total actuator volume per bay (volume between ribs, skins, vertical and aft spar, and rudder hinge line) must be less than 2000 in³. Though the bays near the tip of the tail are the smallest, it was determined that the 1/4 of the volume of the bay at the 1/3 span location is a reasonable constraint to apply. This would allow the AFC actuators to be spatially integrated in the bays that are likely to house the rudder actuators. Assuming that some level of AFC actuator variation is permissible along the span, the actuators could be varied to be smaller near the tip if required.
- The total actuator span (number of actuators multiplied by the width of the actuators) must be less than 90% of the span. This is a relaxed requirement that is analogous to the width requirement for the synthetic jets. The critical linear dimensions are expected to be far less constraining for the sweep jet actuators, so the requirement is set with the objective of being able to install the actuators in a single row along the span of the rudder hinge line.

6.2.2. Sweep Jet AFC System Properties

Sweep jet AFC systems were characterized using the assumptions mentioned above over the range of momentum coefficients, blowing ratios, and number of actuators provided in Table 2. The system characteristics that result are compared against the design constraints in Figure 23 to Figure 26. The shaded areas indicate areas outside of the design space due to the relevant constraint for the figure. Viable configurations (C_{μ} , C_b , n combinations) are indicated with a solid circle symbol to highlight where other design constraints are limiting the design space. Histograms for all viable AFC configurations are also included to provide insight into the most-likely characteristics. The mass flow, chamber pressure, and duct diameter are independent of the number of actuators, where the actuator volume and net actuator span are dependent on the number of actuators.

Figure 22 shows that the pressure of the available APU air limits the maximum blowing ratio that can be obtained to be just under 7.5.

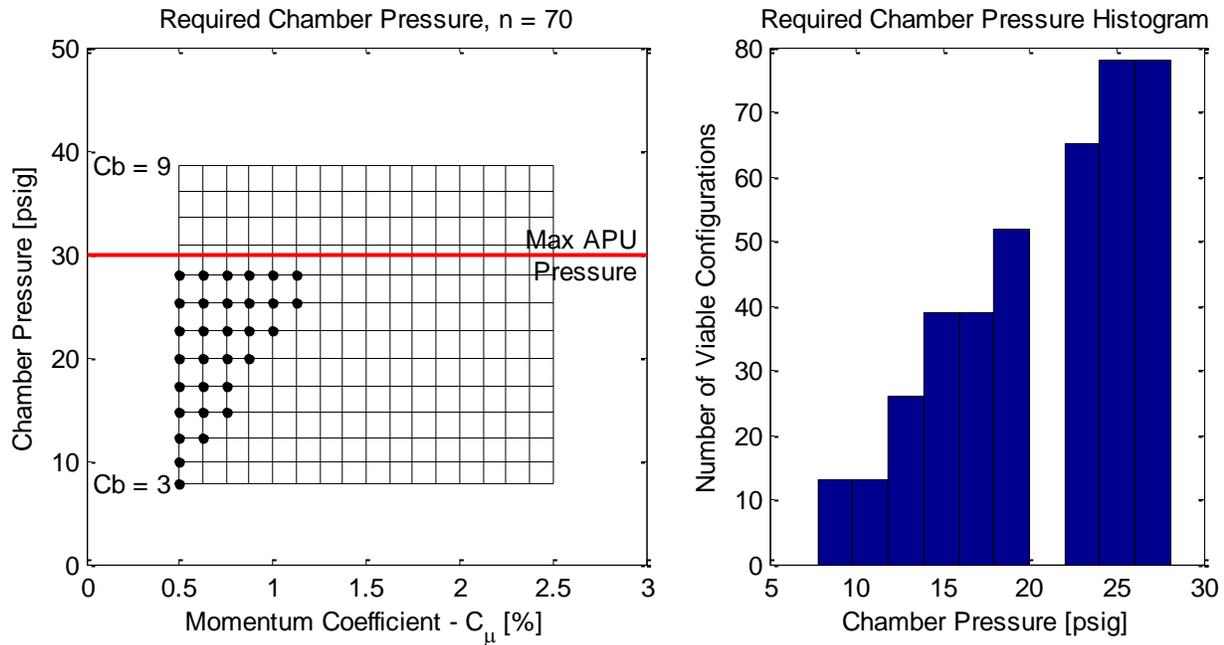


Figure 22: Sweep Jet AFC System Required Chamber Pressure (n=70)

Figure 23 shows the APU mass flow capability is a limiting factor for the sweep jet AFC system, eliminating high momentum coefficients and low blowing ratio configurations. Figure 24 shows a similar impact to the design space, an expected trend given that the APU duct diameter would be sized to limit Mach number in a similar fashion as the duct for the AFC system.

Minimizing the required momentum coefficient is beneficial to system design, lowering both mass flow and duct diameter requirements. Momentum coefficient is ultimately expected to be set based on full-scale AFC performance capabilities. Increasing the blowing ratio would result in increased chamber pressure, as well as decreased mass flow demands and duct diameter. For this reason, the AFC system assessed for the NPV trade is assumed to have the highest possible blowing ratio within the limits of the APU capability ($C_b = 7.0$). Interrogating the data at a fixed blowing ratio of 7.0 shows that the viable C_μ range is limited to approximately 1.125%. The number of actuators used will be a balance of system reliability, weight, and potentially system efficiency. Should the high jet velocities related to this blowing ratio lead to reductions in effectiveness, these velocities (and therefore C_b) can be reduced, but maximum C_μ will also be reduced. The impact of such changes on system integration can be deduced from the figures.

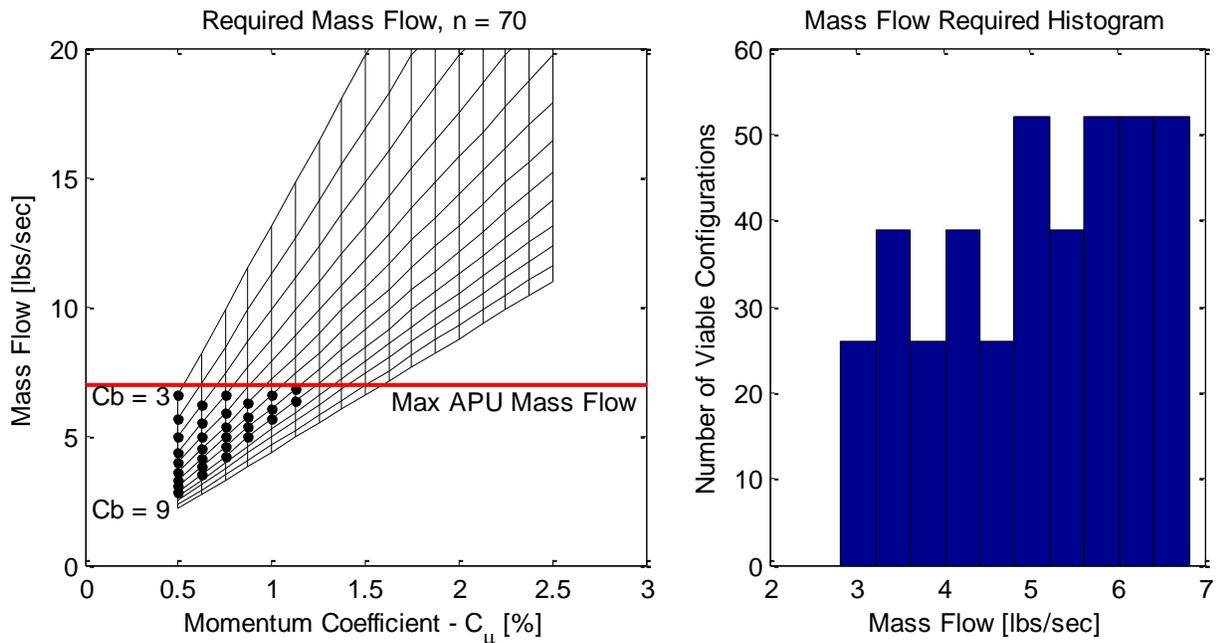


Figure 23: Sweep Jet AFC System Mass Flow Requirements (n=70)

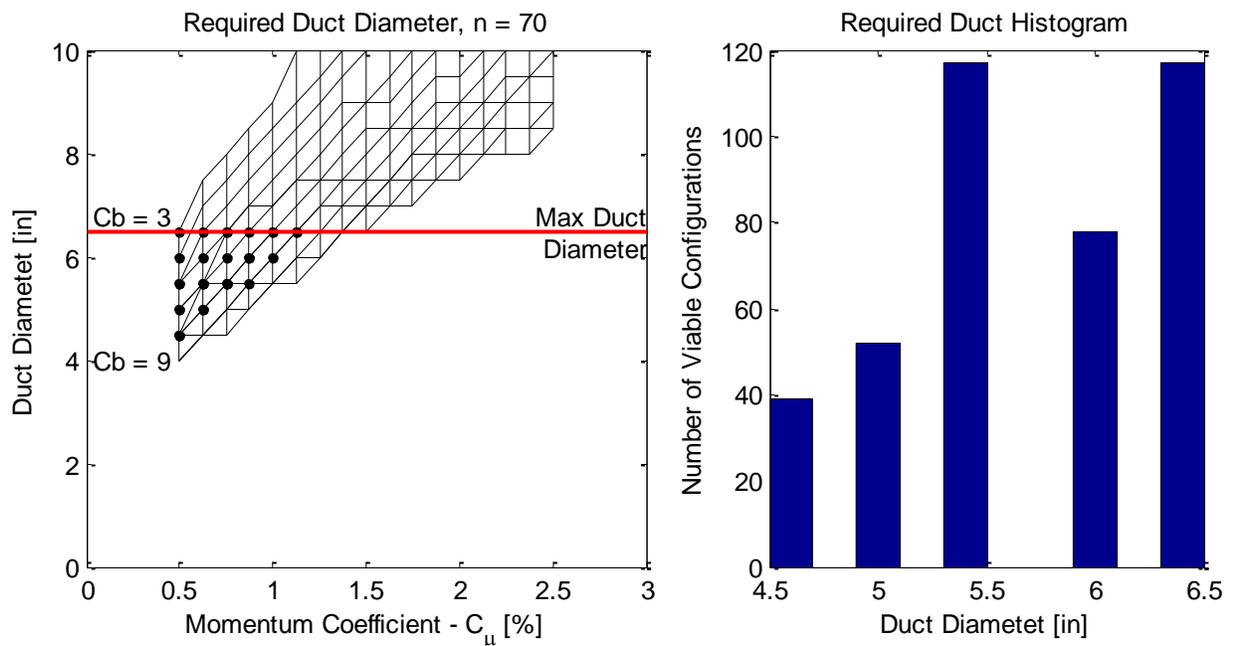


Figure 24: Sweep Jet AFC System Required Duct Diameter (n=70)

Though the actuator volumes and net actuator spans are both dependent on the number of actuators, due to their lack of impact on the design space, the most critical configurations are shown in Figure 25 and Figure 26. A low number of actuators is critical for volume, where a high number of actuators is critical for net actuator span.

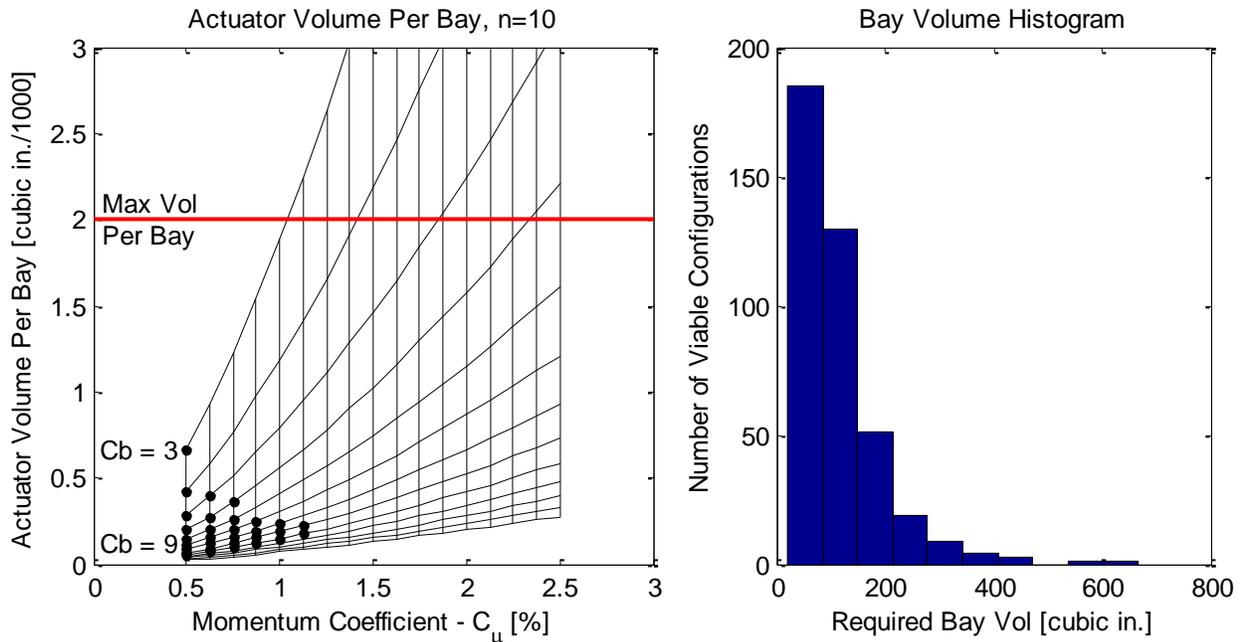


Figure 25: Sweep Jet AFC System Actuator Volume Per Bay (n=10)

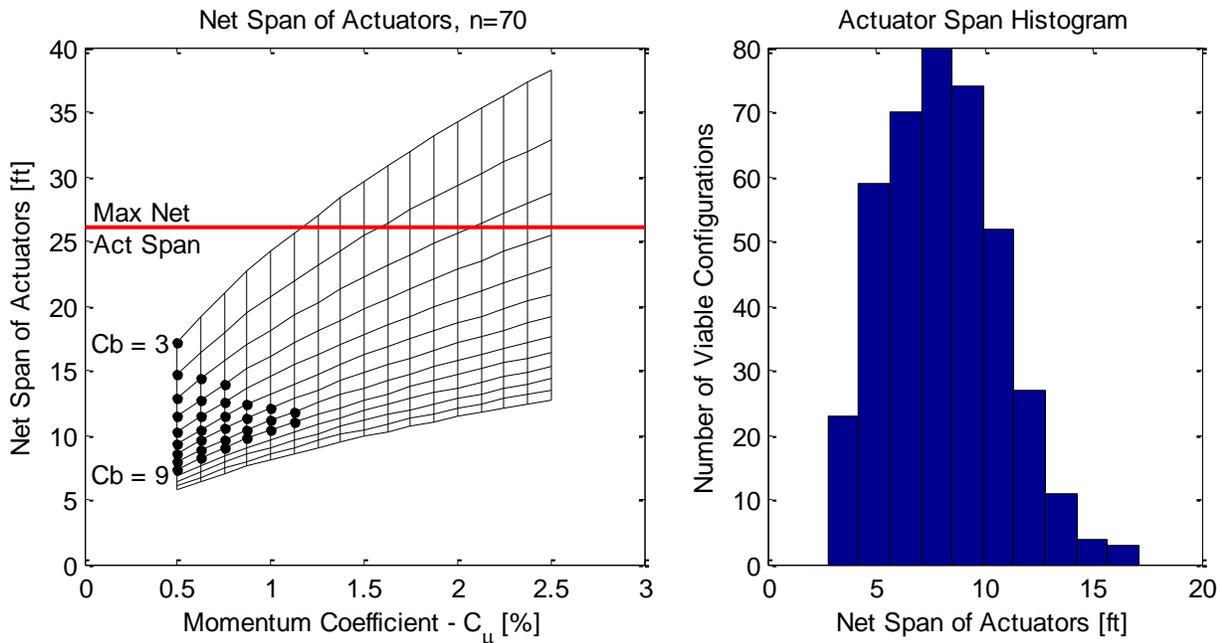


Figure 26: Sweep Jet AFC System Net Actuator Span (n=70)

It was earlier assumed that losing a small amount of actuators (2-3) would not degrade the system performance. This assumption may no longer be valid if the total number of actuators was as low as 10. Figure 27 shows weights for the viable configurations with the fixed blowing ratio discussed above ($C_b = 7.0$). It illustrates that a reduced number of actuators is optimal for AFC system weight.

To balance need to reduce weight and ensure reliability; the sweep jet AFC system is assumed to use between 20 and 40 actuators. Accordingly, the system weights range from 550 to 800 pounds, depending on the required momentum coefficient. With the required momentum being unknown, the range of flow requirements is significant, with a low end of approximately 3 lbs/sec and a high end approaching the limit of the APU capability, 7 lbs/sec.

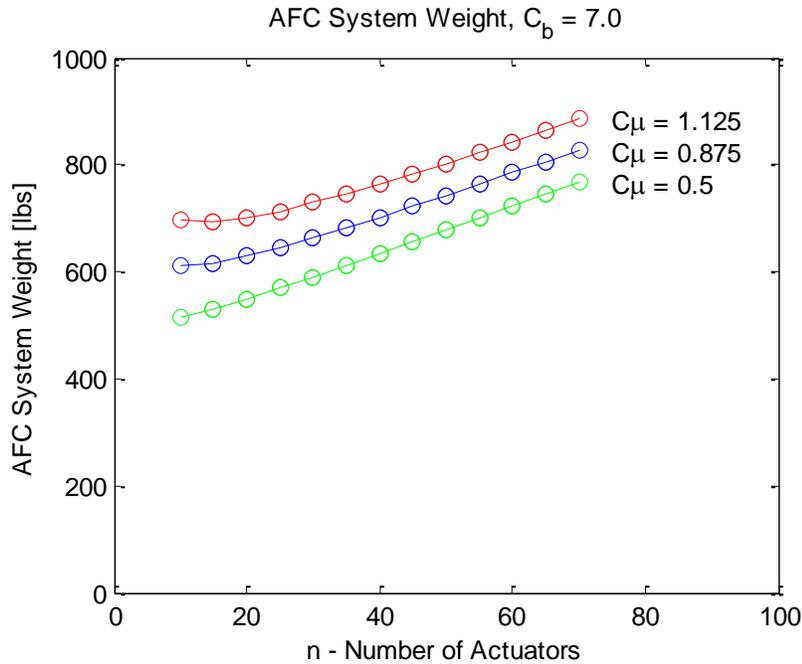


Figure 27: Sweep Jet AFC System Weight

7. Cost Model and System Level Performance Benefits

7.1. Description of Cost/Benefit Model

A trade was conducted to assess the airline and manufacturer’s business case for the active flow control installation on a three-member, twin aisle passenger aircraft family. The trade is conducted as a variation to a baseline. The baseline is a three-member family with the tail sized by the requirements of the shortest member without an AFC system. The study airplane is the same family with an AFC system on the two smaller members only. The sizing condition then becomes the largest member without the AFC system.

The AFC system will be evaluated using a Cost/Benefit model, seen in Figure 28. The trade study will indicate whether value is created or lost by implementing the new technology by comparing a family of commercial aircraft without the AFC system to a family with the AFC system. The key figures of merit will be the NPV (Net Present Value), which is a summation of costs and benefits, adjusted for the time value of money from when they occur to a specified date. The NPV will be expressed in three categories: Manufacturers NPV, Operator NPV and Total NPV.

The Manufacturers NPV represents the present value of the change in development and build cost impacts. The key inputs to this figure are the costs of capital, tooling, engineering, and the recurring build costs. If the Manufacturers NPV is greater than zero we can assume the aircraft builder has an opportunity to financially gain from implementing the AFC system.

The Operator NPV represents the present value of the change in operating costs for the affected fleet of aircraft 20 years from the date of delivery. The inputs that affect Operator NPV are weight, drag, SFC, maintenance, spares and reliability.

The Total NPV is the sum of the Manufacturers and Operators NPV. When positive, this indicates the industry (both the manufacturer and operator) is seeing more value created than is input into the system. The inputs will be expressed in stochastic terms to evaluate uncertainty and sensitivity.

A validated Cost / Benefit model will be utilized with the following built-in assumptions:

- Aircraft Size: A family of mid-size, twin engine aircraft with approximate seat counts of 250 to 350 tri-class seats and 7,200nmi to 8,200nmi range will be assumed.
- Market Size: Using the 2010 Boeing “Current Market Outlook”, or CMO, Reference (11), we will assume a 50% capture of the 7,100 Twin Aisle Market = 3,550 units over a 20 year period.
- Time Context: The AFC system will be installed assuming entry into service (EIS) in 2016 with costs and benefits measured over a 20 year period.
- Aircraft Economics: Average mission length = 3,000nmi, aircraft life = 20 years.
- Manufacturers Economics: NPV will be calculated based on a pre-tax discount rate of 16.6%. This is calculated from pre-tax Weighted Average Cost of Capital (WACC) of 3 large U.S. aerospace companies using a marginal tax rate of 35%. Non-recurring will be spread equally 3 years prior to the first delivered unit.
- The outputs will be in 2011 dollars.

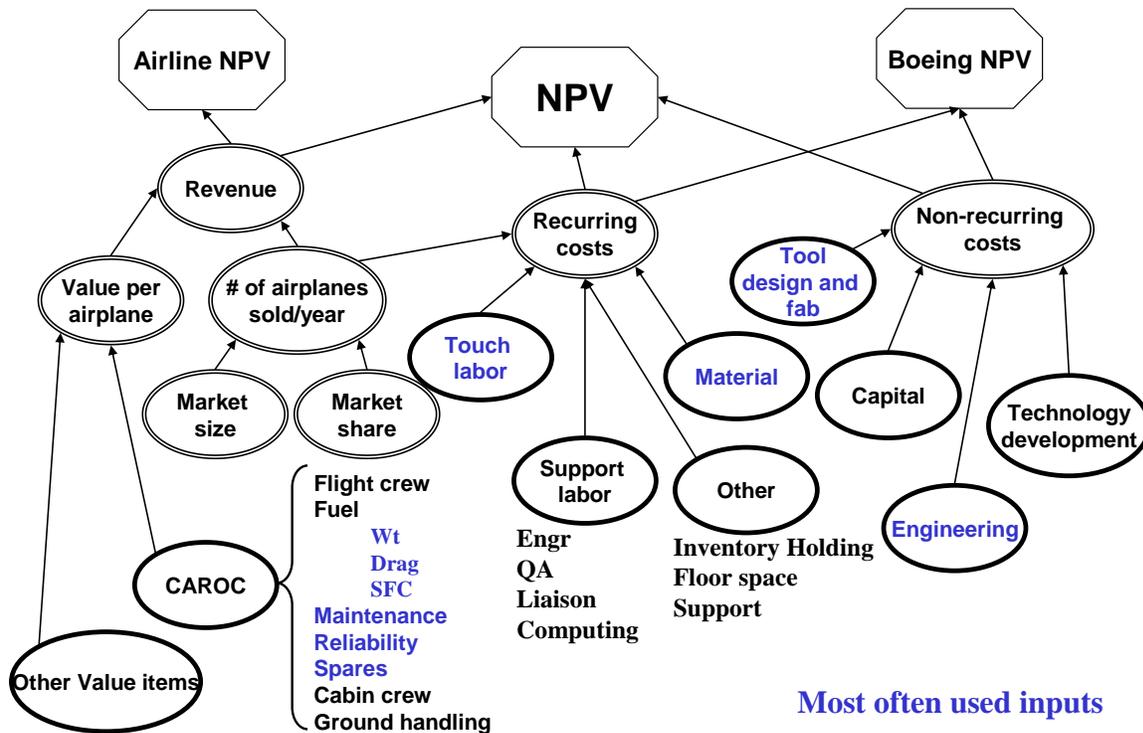


Figure 28: Trade Study Model Inputs

7.2. Synthetic Jet NPV and Performance Benefit

The inputs for the synthetic jet NPV assessment are summarized in Table 3. The weights used are based on the system properties discussed above. A majority of the costs are determined using public-domain estimating techniques, described below, and the drag and SFC benefits are determined using rough order of magnitude engineering estimates.

| Input Parameter | Low | Most Likely | High |
|--|--------------|--------------|--------------|
| Weight Impact – Total | +167 | +600 | +967 |
| <i>Weight Impact – AFC System</i> | +367 | +700 | +967 |
| <i>Weight Impact – Vertical Tail</i> | -200 | -100 | 0 |
| Synthetic Jet System Costs \$ | \$73,000 | 140,000 | \$193,000 |
| Vertical Fin Recurring Cost Reduction \$ | -\$160,000 | -\$80,000 | \$0 |
| Non-Recurring \$ | \$12,000,000 | \$44,000,000 | \$70,000,000 |
| Maintenance Costs \$/year | \$6,000 | \$9,500 | \$13,500 |
| Drag Impact - % | -0.29% | -0.39% | -0.43% |
| SFC Impact - % | 0.054% | 0.071% | 0.104% |

Table 3: Synthetic Jet NPV Input Ranges

7.2.1. Weight

The weight range of viable synthetic jet configurations provided in Section 6.1.2 is 550 to 2,250 lbs for a C_{μ} range of 0.5 to 1.625. The weight range for viable sweep jet configurations provided in Section 6.2.2 is provided for a C_{μ} range of 0.5 to 1.125, as higher momentum requirements are outside of the design space. The costs associated with the AFC systems are directly related to weight, which is proportional to power required. For an equitable comparison of NPVs between the two technologies, the weights need to reflect a consistent range of power requirements. Accordingly, the synthetic jet system weight range is defined using a reduced range of momentum requirements ($0.5 < C_{\mu} < 1.125$). Using this limited range of momentum, the system weight is estimated to range between 550 lbs and 1,450 lbs, with a most-likely weight of 1,050 lbs. These values are factored by 2/3 in the NPV analysis to account for the fact that only the two shortest family members have the system installed.

In addition to the AFC system weight, changes to the weight of the vertical tail itself need to be taken into account. A simple scaling of the vertical tail weight based on the size reduction would estimate the weight savings to be on the order of 400 lbs. Even though the vertical tail is being downsized, the weight is not expected to scale linearly with size, as the vertical tail is expected to carry the same load. Given that the load on the downsized tail is likely acting with a reduced moment arm relative to the root of the tail, reducing the bending moment at the root, some fraction of that weight savings is likely possible. To provide a conservative assessment, a 0 to 200 lb weight savings is used for the vertical tail.

7.2.2. Recurring Costs

Similar to the weights, the recurring cost impacts are also made up of the impact of the vertical tail changes and the AFC system itself. To estimate the recurring costs of both these items using public-domain information, the work of Markish, Reference (12), was leveraged to estimate the labor, material, and ‘other’ costs associated with major airframe parts. The method provides a ‘theoretical

first unit' recurring cost (TFU) and a method for determining the marginal unit cost (MC) based on quantity built (Q) and learning curves that tend to reduce the costs as production progresses, based on Equation 12.

$$MC = TFU \times Q^{\ln(s)/\ln(2)}$$

Equation 12

The AFC system was treated as a brand new system (first unit used $Q = 1$). Using the suggested recurring costs per pound, adjusted for inflation, the recommended learning curves were applied and the average AFC system recurring costs were determined on a per pound basis. Over the assumed production run of 3550 airplanes, 2/3 of which have the AFC system installed, the AFC system is estimated to have a cost of \$200 per pound. Using the weights prescribed above, the recurring costs for the AFC system range from approximately \$110,000 to \$290,000 per airplane, with a nominal cost of \$210,000. As with the AFC system weight, these recurring costs are only applied to 2/3 of the airplanes in the NPV analysis.

The vertical tail was treated as a known empennage component, thus the learning curve credit is minimal (first unit used $Q = 1000$). Since the vertical tail component represents a cost savings, this methodology is conservative as it lowers the average cost per pound. Again, using the suggested recurring costs per pound, adjusted for inflation, the recommended learning curves were applied and the average vertical tail recurring costs were determined on a per pound basis. Over the assumed production run of 3550 airplanes, the vertical tail weight savings will result in an \$800 per pound savings. Using the vertical tail weights discussed above, the costs savings range from \$0 to \$160,000, with a nominal savings of \$80,000.

7.2.3. Non-Recurring Costs

The non-recurring cost excludes research costs required to bring the technology to a state of application readiness. The rationale is that costs up to this point are common across multiple implementations and typically are funded from sources other than a specific airplane program.

Non-recurring costs were also estimated using information from Reference (12) by breaking the contributions down into AFC system and vertical tail contributions. The non-recurring cost breakdowns are more straight-forward, with systems costing \$48,000 per pound and the empennage costing \$74,000 per pound, after accounting for inflation. The low, nominal, and high weights were used with these costs to determine the net non-recurring costs presented in Table 3.

7.2.4. Maintenance Costs

The maintenance costs that are included in the NPV study are the maintenance costs of the AFC System itself and the costs of maintaining the APU with increased usage. Both are estimated using public-domain information in a conservative fashion to protect against underestimates due to the difficulty in predicting maintenance costs for new systems.

Annual maintenance costs of the AFC system are estimated using the International Air Transport Association's Airline Maintenance Cost Executive Commentary, Reference (13). The wide-body annual aircraft maintenance costs provided for Boeing airplanes are approximately 2% of the list prices that can be found on Boeing's public website, Reference (14). To provide some margin in the assessment given that the method is rough and the technology is new, this relationship was doubled

to 4% and applied to the manufacturer's recurring costs for the AFC system to develop the range of annual maintenance costs for the AFC system. This results in costs ranging from approximately \$4,000 to \$11,000 per year per airplane, with a nominal value of \$8,000.

Roskam, Reference (15), provides methods for estimating engine maintenance costs by estimating both labor and material costs. These methods are applied to the APU, with a nominal APU power capability of 1,700 hp, based on the capability of the Honeywell HGT1700 APU developed for and employed on the Airbus A350 XWB. The methods are used to determine a maintenance cost per operating APU hour. The added necessity of having the APU on through the early part of climb-out and turned back on during approach increases the APU utilization by an estimated 30-60 minutes per day, assuming two flight cycles per day. This results in an approximate maintenance cost increase of \$4,000 to \$8,500 per year per airplane, with a nominal of \$6,500.

Combining the AFC system and APU maintenance costs to 2/3 of the family, a range of \$6,000 to \$13,500 with a most likely value of \$9,500 per year per airplane is applied.

7.2.5. Drag

On all three family members the vertical fin reference area was reduced to 470 ft² from 550 ft². The mid mission cruise drag benefit was estimated to be approximately 0.40% based on the reduction in wetted area. A benefit range of 0.3% to 0.45% was considered reasonable.

As previously discussed, some small number of missions may require that the APU be left on for the duration of the flight to ensure that the APU is available for the landing. This would be the case on landing-field length critical missions, where speed penalties associated with the APU failing to start would result in a diversion to an alternate airport. For mid-size long-range airplanes, this is expected to be needed on less than 1% of the missions. On such missions, the APU could remain on for the duration of the flight, incurring a drag penalty due to having the APU inlet open during flight. Applying this penalty to 1% of the flights is expected to reduce the average drag benefit by a small amount, changing the benefit to 0.29%, 0.39%, and 0.43% for the low, most-likely, and high drag benefits.

7.2.6. Specific Fuel Consumption

The APU being operational for additional flight time needs to be accounted for by applying fuel consumption penalties. For flights where the APU is turned off for the majority of the mission, the additional fuel to have the APU running for 15-30 minutes is estimated at 75-150 lbs. For flights where the APU is running for the entire time a 750 lb fuel penalty is estimated. With the average mission length of 3,000 miles, approximately 100,000 pounds of average mission fuel is estimated using the data available in Reference (16); the APU fuel burn is approximately a 0.075% to 0.15% penalty on normal missions and 0.75% on missions where the APU is left on for the entire mission. These penalties are weighted in the same way that was done for the drag benefit – 1% of missions use the penalty associated with the APU being on for the entire mission, 99% of missions use the penalty with the shorter duration APU usage. For use in the NPV analysis, applying these penalties to 2/3 of the fleet results in a 0.055% - 0.104% SFC increase, with 0.071% used as the most-likely case.

7.2.7. Results

Using the input ranges of Table 3, the analysis shows that there is a reasonable likelihood that application of the synthetic jet AFC system would result in an NPV benefit, indicated by a positive value. Manufacturing, Operating, and Net NPV results for the most likely scenario are:

- Manufacturing Cost NPV (Most Likely): -\$71M
- Operating Cost NPV (Most Likely): \$109M
- Net NPV (Most Likely): \$38M

The contributors to NPV for the most-likely inputs for synthetic jets are shown in the Pareto chart in Figure 29. The drag benefit is the only item bringing benefit to NPV, with weight, maintenance, SFC, non-recurring, and recurring costs all bringing down-sides to the NPV. The weight is the largest down-side contributor to the NPV.

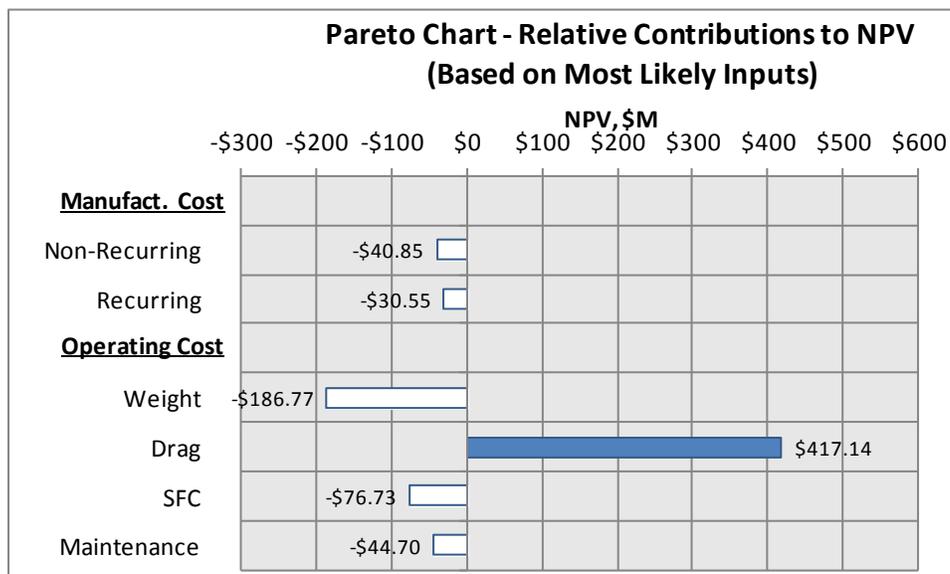


Figure 29: Comparison of Relative Contributions to NPV for Most Likely Inputs – Synthetic Jets

The stochastic results, shown for Manufacturing, Operational, and Net NPV in Figure 30 to Figure 32, show the likelihood of the synthetic jet AFC system being a benefit to both the customer and manufacturer based on the low-to-high range of inputs used. The Manufacturing NPV indicates that there is a 100% certainty that the system will result in additional manufacturing costs – an expected conclusion. The operating costs show that it is nearly certain to be a benefit to the operators. The Net NPV indicates that there is approximately a 50% chance that the net value of the system will be positive, allowing the manufacturer to recoup the manufacturing costs through their business model.

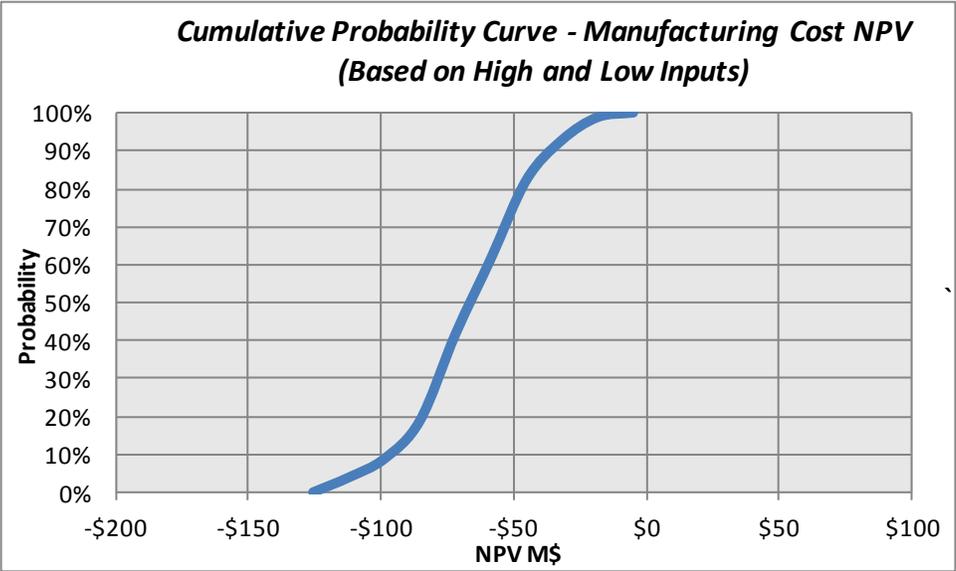


Figure 30: Manufacturing Cost NPV - Cumulative Probability - Synthetic Jets

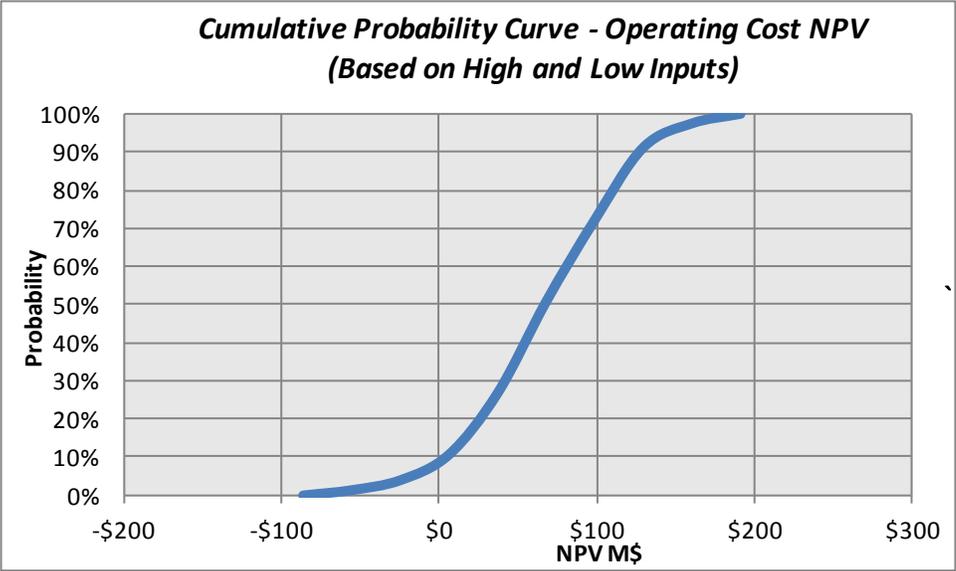


Figure 31: Operating Cost NPV - Cumulative Probability - Synthetic Jets

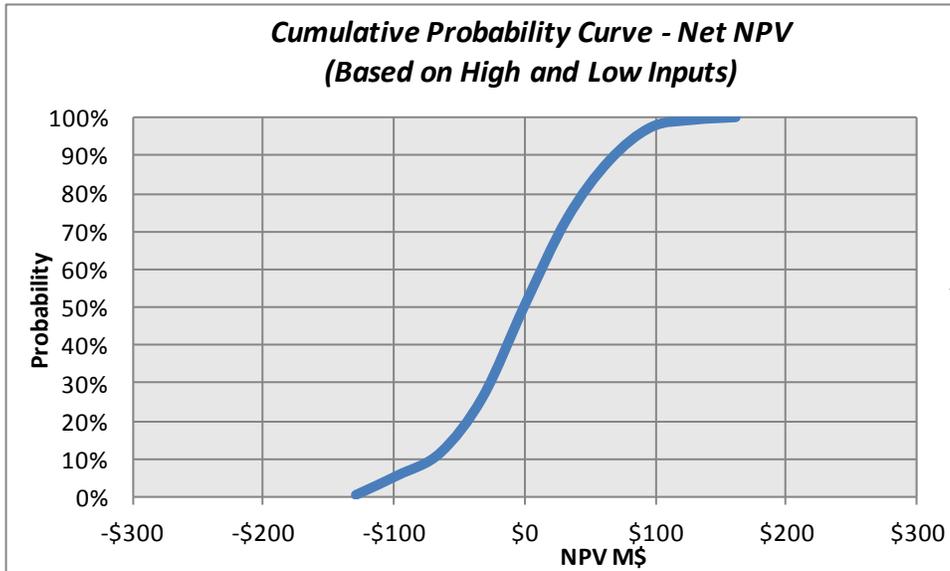


Figure 32: Net NPV - Cumulative Probability - Synthetic Jets

The drivers to the uncertainty in the NPV stochastic analysis are shown in Figure 33, with weight being the largest driver. This “tornado chart” is developed by setting all the inputs to their most likely values, then independently varying each input from its low to high value and calculating the range of NPV’s. It should be noted that while drag was by far the largest contributor to the total benefit, weight is the largest contributor to the uncertainty. In this case, the drag impact was relatively well understood. Knowing the required momentum and jet velocity required to produce the required aerodynamic effect would help reduce the uncertainty.

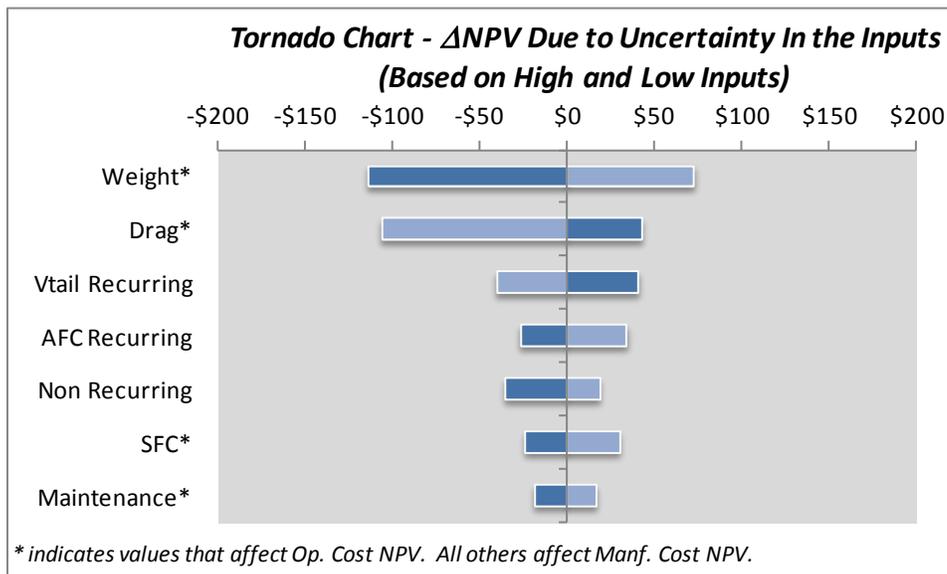


Figure 33: Uncertainty Analysis - Synthetic Jets

Given that conservative estimates were used to define AFC system characteristics and costs, implementation of a synthetic jet AFC system as described above would have a reasonable likelihood of resulting in a net benefit for NPV. A better understanding of the weight and recurring

costs would be most beneficial to reducing the uncertainty in the Cost/Benefit analysis, which requires a better understanding of the AFC performance required to provide the aerodynamic benefit.

The operational costs have a high likelihood of being a benefit to the airplane operators. This is largely driven by the fuel savings. A first-order estimation of the fuel savings is developed using the Breguet range equation, re-arranged to estimate fuel burn in Equation 13.

$$W_f = W_0 \left(1 - e^{\frac{-RC}{VL/D}} \right)$$

Equation 13

Where, for the baseline airplane

- W_0 , the initial weight, is estimated at 500,000 lbs, consistent with the baseline airplane
- R , the range, is set to 3,000 nmi, based on the average mission
- C , the specific fuel consumption, is set to 0.5, consistent with modern turbofan engines
- V , the cruise speed, is set to 800 ft/s, consistent with a high-altitude cruise close to $M=0.84$
- L/D , the lift to drag ratio, is estimated at 19.0, consistent with large transport category aircraft

The initial weight, specific fuel consumption, and lift to drag ratios are set for the study airplane based on the most-likely values used in the NPV assessment and the resulting fuel savings is determined. Over a year of operations, a single airplane is expected to save approximately 80,000 lbs (11,900 gallons) of fuel with the synthetic jet system.

7.3. Sweep Jet NPV and Performance Benefit

The inputs for the sweep jet NPV assessment are summarized in Table 4. These inputs are developed using the same build-up processes described in Section 7.2.1 to Section 7.2.6. This process relies heavily on the weight estimates for the AFC system and the vertical tail. The differences in the NPV analysis stem from the weight differences between the two systems. Weights and costs associated with the vertical tail are identical, as both AFC systems have the same estimated impact on vertical tail properties, namely size. There will be some detailed structural differences in how the two types of systems are implemented (e.g. cutouts in structural members for plumbing/wiring), but they are relatively minor and are assumed to be rolled into the weight estimates for the two systems. The drag and SFC impacts are also unchanged for the sweep jet AFC system.

| Input Parameter | Low | Most Likely | High |
|--|--------------|--------------|--------------|
| Weight Impact – Total | +167 | +333 | +533 |
| <i>Weight Impact – AFC System</i> | +367 | +433 | +533 |
| <i>Weight Impact – Vertical Tail</i> | -200 | -100 | 0 |
| Sweep Jet System Costs \$ | \$73,000 | \$87,000 | \$107,000 |
| Vertical Fin Recurring Cost Reduction \$ | -\$160,000 | -\$80,000 | \$0 |
| Non-Recurring \$ | \$12,000,000 | \$25,000,000 | \$39,000,000 |
| Maintenance Costs \$/year | \$6,000 | \$7,500 | \$10,000 |
| Drag Impact - % | -0.29% | -0.39% | -0.43% |
| SFC Impact - % | 0.054% | 0.071% | 0.104% |

Table 4: Sweep Jet NPV Input Ranges

7.3.1. Results

Using the input ranges of Table 4, the analysis shows that there is a reasonable likelihood that application of the sweep jet AFC system would result in an NPV benefit. Manufacturing, Operating, and Net NPV results for the most likely scenario are:

- Manufacturing Cost NPV (Most Likely): -\$27M
- Operating Cost NPV (Most Likely): \$170M
- Net NPV (Most Likely): \$143M

The contributors to NPV for the most-likely inputs for sweep jets are shown in the Pareto chart in Figure 34. The drag benefit is the only item bringing benefit to NPV, with weight, maintenance, SFC, non-recurring, and recurring costs all bringing down-sides to the NPV. As with the synthetic jet system, the weight of the sweep jet system is the largest down-side contributor to the NPV.

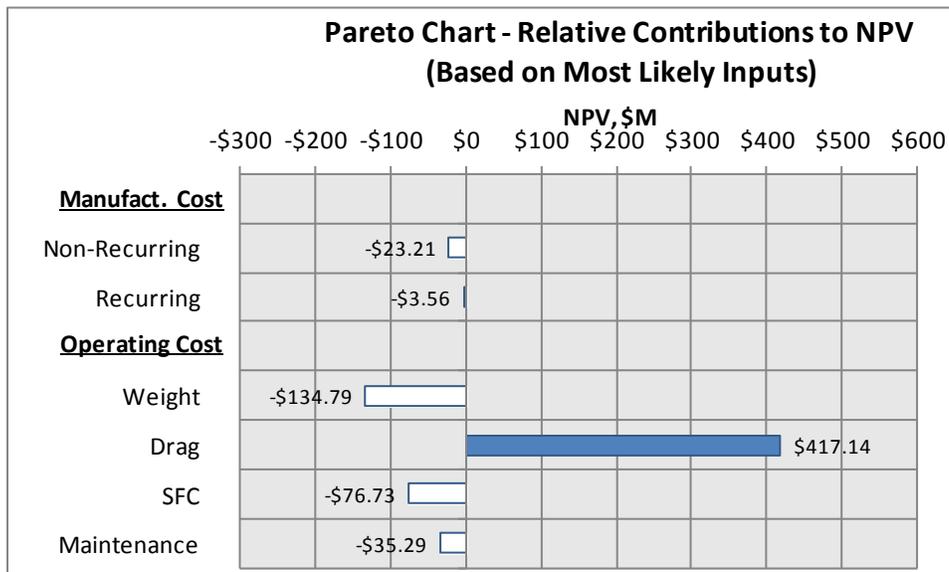


Figure 34: Comparison of Relative Contributions to NPV for Most Likely Inputs – Sweep Jets

The stochastic results, shown for Manufacturing, Operational, and Net NPV in Figure 35 through Figure 37, show the likelihood of the sweep jet AFC system being a benefit to both the customer and manufacturer based on the low-to-high range of inputs used. The plots are provided using the same scales as those used in Section 0 to allow for easy comparisons of the two technologies. The Manufacturing NPV is virtually all negative, as would be expected, though the analysis does show that there is a small chance that the recurring cost savings from the vertical tail could outweigh the recurring cost penalties of the sweep jet system. The operating costs show that the sweep jet AFC system is sure to be a benefit to the operators. The Net NPV shows that the sweep jet AFC system is certain to bring positive net NPV based on the defined AFC system. An analysis and comparison of these results to those of the synthetic jet AFC system is provided in Section 8.

Over a year of operations, a single airplane is expected to save approximately 104,000 lbs (15,500 gallons) of fuel with the sweep jet system.

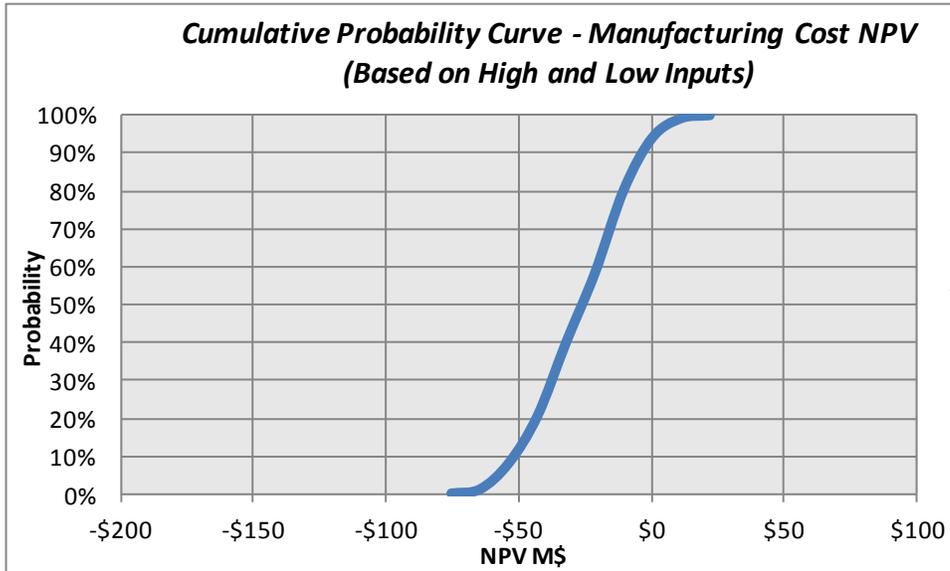


Figure 35: Manufacturing Cost NPV - Cumulative Probability - Sweep Jets

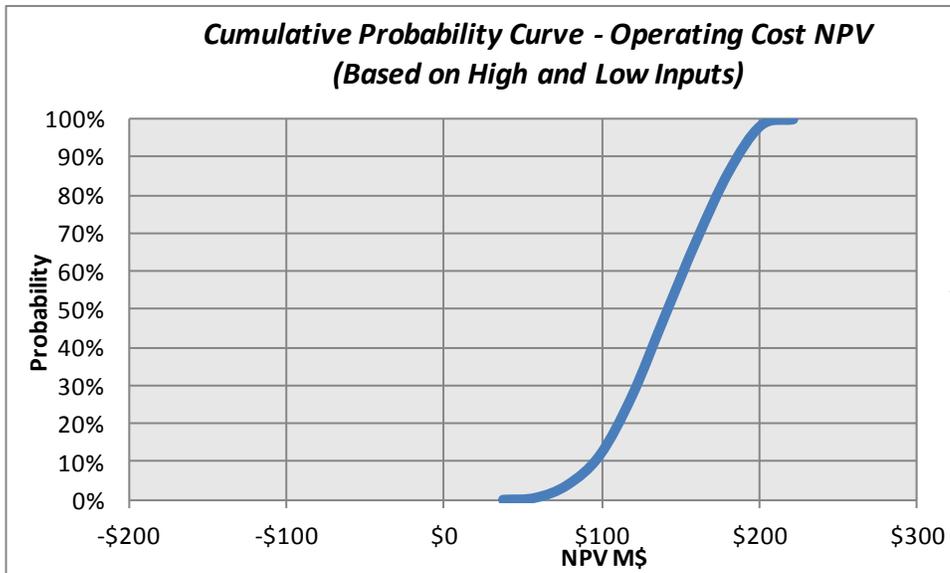


Figure 36: Operating Cost NPV - Cumulative Probability - Sweep Jets

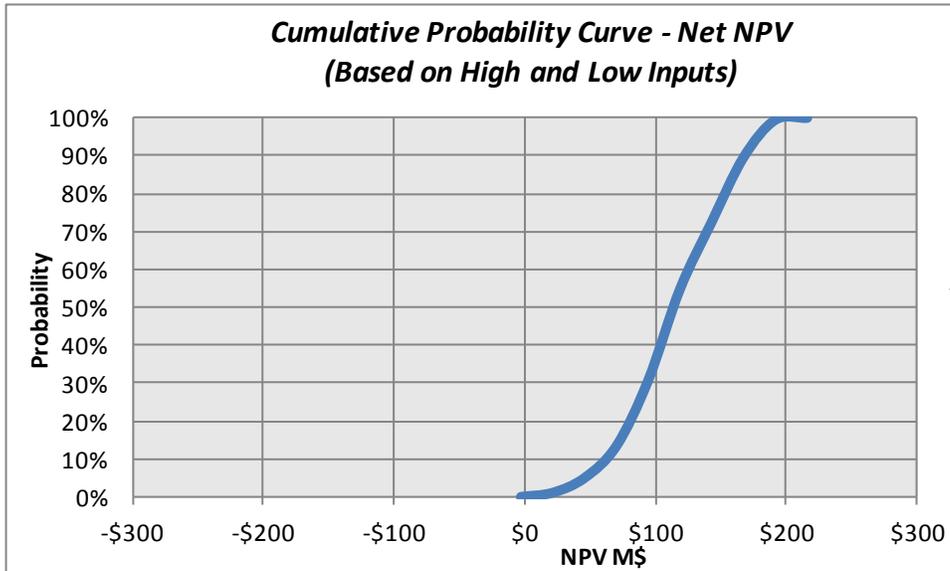


Figure 37: Net NPV - Cumulative Probability - Sweep Jets

The tornado chart provided in Figure 38 indicates that the range of drag improvements is the primary driver to the uncertainty for the sweep jet system, different from the synthetic jet system where the weight range was the primary driver for the uncertainty range. This is a result of the smaller range of weights associated with the sweep jet system, which also cascades into smaller ranges of non-recurring and recurring costs associated with the AFC system.

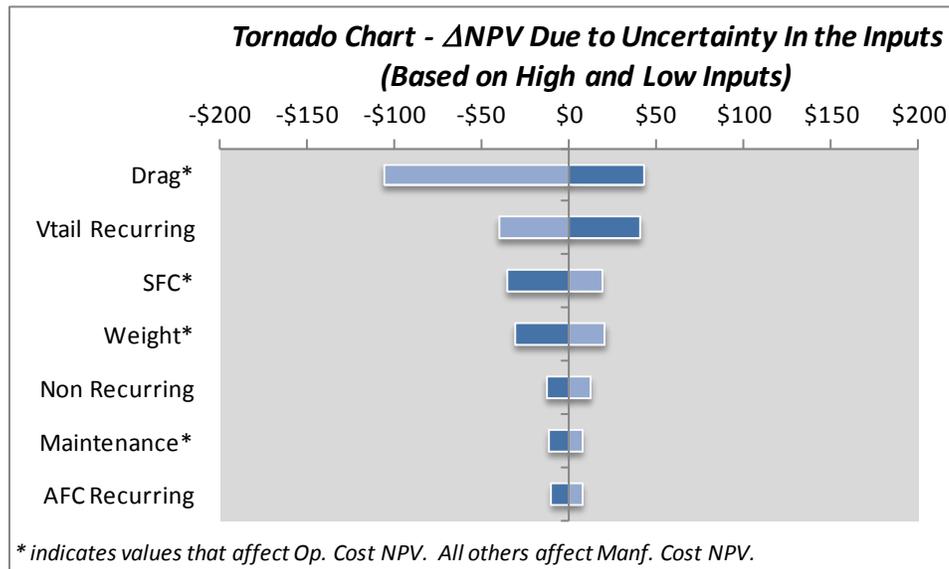


Figure 38: Uncertainty Analysis - Sweep Jets

8. Analysis and Conclusions

8.1. Evaluation of Study Results

The NPV assessments for both the synthetic jet and sweep jet systems indicated a net positive contribution to the baseline family of airplanes. In both cases, the operational benefits associated with the reduction in airplane drag that comes about as a result of the reduced tail size more than outweigh the negative impacts of system implementation. Fortunately, this one benefit is relatively easy to compute with reasonably high level of confidence, and it is significant. The challenge lies in accurately representing the implementation costs.

As part of these assessments, ranges of values for several key parameters were evaluated to assess the effects of uncertainty in these parameters on NPV. The nominal value of each was purposely biased toward conservatism in order to avoid an overly optimistic NPV answer, and yet a positive outcome was still received. This return was greater for the sweep jet system where it was positive across the range of input probabilities. The return was lower for the synthetic jet system, with only about a 50% chance of having a positive outcome.

It's important to note that many assumptions were made along the way for both systems. The risks associated with many of these assumptions are not accounted for in the probabilistic NPV analysis, particularly on the negative side of the ledger. Therefore, it's worth re-examining the assumptions for each type of system in order to understand the rest of the story. This will be done for each system independently. For each, the discussion will be broken into four categories: tail sizing, operational, actuator, and integration. It is hoped that this will serve to highlight the technical challenges associated with the study and how they differ between the two actuation approaches, as well as point out how these challenges may impact the conclusions that can be drawn.

8.1.1. Synthetic Jet AFC System

8.1.1.1. Tail Sizing Assumptions

The critical sizing scenarios for the vertical tail were determined to be associated with engine inoperative situations on takeoff and approach. A complete AFC system failure in combination with an engine failure in these flight phases must be less than $10E-9$. This implies that the probability of AFC system failure alone can be much greater than this value, which in turn means that it is easier to architect a system which has adequate availability. The relatively simple system defined for this study with half of the actuators powered and controlled by separate LRUs is enabled by this lower availability requirement, and it is a key driver in keeping integration weight and cost down. This critical sizing scenario is deemed sound for this study.

There is a risk of reaching other sizing limits elsewhere in the operational envelope once the critical sizing criterion is addressed with AFC. The addition of AFC makes the tail operate as if it is bigger than it actually is during the small portions of the flight envelope where the assumed critical design criterion comes into play. Throughout the rest of the flight envelope, the tail is unaugmented, and therefore has less capability than that of the larger baseline tail. For example, a smaller tail will result in lower high speed directional stability than the baseline. At some level of tail size reduction, this criterion will become the limiting factor, and no further tail size reductions will be possible without addressing this limitation. However, limitations associated with high speeds are not easily

addressed with the synthetic jet AFC system defined here as blowing ratios would be significantly reduced and the operational window in which adequate system availability must be maintained is significantly larger. For the level of tail size reduction assumed in this study, it is felt that that other sizing conditions do not become limiting. However, it is also felt that further sizable reductions in tail size would not be possible without other sizing criteria becoming limiting.

8.1.1.2. Operational Assumptions

The assumption that the system will be turned on when needed as opposed to being turned on ahead of time periods when it might be needed is a sound one for the synthetic jets. Having them on at full power as part of normal operations would almost certainly generate unacceptable noise issues. In addition, it is felt that it is not unreasonable to assume that the actuators could be turned on and become effective sufficiently quickly to meet system responsiveness requirements.

The assumption that the system testing required to minimize the impact of latent failures on system availability can be done with sufficiently low noise levels by using lower power settings and only testing a limited number of actuators at a time appears reasonable. It is also deemed reasonable that such testing can be done in manner that does not significantly impact pilot workload. However, it is worth pointing out that the details of a synthetic jet health monitoring system have yet to be developed.

8.1.1.3. Actuator Assumptions

Most of the testing with synthetic jet actuators has been done with relatively small actuators, on relatively small scale models and at relatively low airspeeds. Increasing scale presents a host of challenges, most of which get more onerous as the assumed level of system output increases. For example, as C_{μ} increases, so does the number of actuators and/or their size. For the nominal assumptions of this study, the actuators were quite large relative to those tested to date, which presents two issues. The first is an integration concern about whether they can be integrated harmoniously with the other structural and systems hardware within the trailing edge bays of the vertical tail. This will be addressed in more detail below. The second is related to the relatively small amount of data available for larger scale actuators. This leaves us without firm answers to many important questions. Can we predict the effectiveness of these larger devices? Can we predict the efficiency and power consumption for them? Can we predict the losses that might result from non-optimal exit geometries that result from packaging constraints associated with larger actuators? These questions will remain unanswered until larger actuators with improved output are available to test.

There are also issues that remain for synthetic jet actuators of any size. While it is believed that they can be designed to operate throughout the entire temperature range encountered by an airplane as well as deal with moisture concerns by using integral heaters to avoid problems with ice, the issue of longevity in these environments is still not well understood. The importance of this issue cannot be underestimated. It has been assumed that there will be maintenance cost associated with the actuators and other system components. However, no penalties have been applied for an impact to schedule reliability. It is simply assumed that the system cannot have a measurable impact on it. If it did, very large operator costs would rapidly accrue and customer satisfaction would be diminished. Presently, data do not exist to support the longevity assumptions, but it is a hurdle that must be cleared to implement such a system.

8.1.1.4. *Integration Assumptions*

As alluded to above, there is a concern as to whether the larger number/size of actuators required for higher C_{μ} 's could be accommodated. While some initial layout work has been done and some crude volumetric and depth constraints have been incorporated into this study, it's clear that a system packaging that allows the components to co-exist in the trailing edge bays of the vertical tail with required hardware such as structural members and rudder actuators will be one of the primary challenges for a synthetic jet system. If it turns out that lower C_{μ} 's and therefore a smaller number/size of actuators can meet effectiveness requirements, many of these issues will be mitigated. If a larger actuator volume is required, risks rise considerably. If there are considerable conflicts in certain areas of the span, resulting compromises in actuator positioning could negatively impact overall system effectiveness and efficiency.

In addition to packaging challenges, power requirements also become greater at larger C_{μ} levels. For this study, two generators on the APU are the assumed power sources. It is assumed that the AFC system would not impact the required sizing of those generators, and that other less critical power loads on the system could be shed to free up power for the AFC system should it be needed. It was also assumed that the generator sizes would be fairly large, which is consistent with a new airplane with a systems architecture that relies more on electrical power and very little on bleed air. If the target airplane did not have sufficient electrical power available from the APU, the APU generation capability would have to be increased, along with its weight and cost, or power would have to be drawn from the main engine generators, at an increased weight and cost due to the increased distance between the power source and need. While there is potential for reducing power demands through reductions in duty cycle, there's a lack of relevant data at larger scales to confirm that. There is also the possibility that the duty cycle will have to increase from the nominal 70% to 100% to achieve the required effectiveness levels, which would further increase power demands. One more potential issue for high-power-draw synthetic jet systems is dealing with the heat that they could create. While their intended use should not have them turned on for long enough to create a concern (except for potentially locally around the LRU's), the system design would have to have provisions for not failing in the activated state.

A range of assumptions have been made regarding the estimated weight impacts of system incorporation. The assumptions regarding the weight of the fin are deemed reasonable and somewhat conservative. Weight estimates for the synthetic jet system hardware are a function of some simplistic assumptions. Their accuracy likely decreases with increasing system size.

The control system and associated LRU's responsible for managing the operation of the actuators is considered to be relatively straightforward in design.

8.1.2. Sweep Jet AFC System

8.1.2.1. Tail Sizing Assumptions

The tail sizing assumptions for the sweep jet configured tail are identical to those used for the synthetic jet configured tail. Therefore, the same amount of side force augmentation is assumed to be required for both. However, this study suggests that more AFC control authority would be possible for the sweep jet system than with synthetic jets, within the assumed constraints. This would imply that the chance of being able to satisfy the side force requirements is greater with sweep jets is greater than with synthetic jets should the required C_{μ} 's end up at the higher end of the spectrum.

8.1.2.2. Operational Assumptions

While the character of the noise generated by the sweeps jets is different than that of synthetic jets, they can still be quite loud, particularly at higher jet velocities. This is why the operational assumptions for the sweep jet system are similar to those for synthetic jets. They must not be turned on for normal operations to avoid noise issues, and therefore must be configured to activate only in the event of an engine failure within a certain low speed regime.

In order to ensure short response times, it is assumed that the system is pre-pressurized and that valves at each actuator on the appropriate side of the rudder open in the event of system need. While there is additional complexity with this approach associated with arming/pressurizing the system in advance and having additional valves, the advantage (in addition to lower noise) is that only half of the mass flow is needed, as an approach with the system preemptively turned on would have to blow on both sides of the tail to be prepared for either engine failing. A system that can react to the engine failure need only blow on one side.

Lastly, the same logic assumed with the synthetic jet system regarding the application of a low-intrusiveness, low-noise testing procedure is applied here as well. This would likely amount to a pressure transducer downstream of each valve that can verify that an appropriate amount of air is passing through the valve.

8.1.2.3. Actuator Assumptions

There are far fewer potential roadblocks in the path of a full scale sweep jet actuator implementation. The actuators can be built and bench tested today. What is less understood is how the requirements of a sweep jet system such as actuator size, spacing, jet velocity, inlet pressure, mass flow rate, and overall C_{μ} for a full scale system differ from sub-scale testing. Uncertainties in these parameters translate directly into NPV uncertainties, not unlike for synthetic jets. However, it is known that these systems are currently capable of higher jet velocities and C_{μ} 's than those of synthetic jet systems. In addition, there are no technical obstacles to obtaining data at larger scale.

These actuators should have no issues operating throughout an airplane operating envelope. With the assumption that the devices will be heated to mitigate any potential ice-related problems, they should be self-clearing of fluids. Some additional testing to ensure that debris will not collect in the lower feedback branches of the actuator and inhibit the sweeping action is likely required. Actuator longevity should also not be an issue, as the actuators themselves have no moving parts. The assumed imbedded heaters, the upstream valves, and presumably health monitoring pressure sensors

are the likely maintenance items. The risk of the actuators or related components measurably impacting dispatch reliability is believed to be low.

8.1.2.4. Integration Assumptions

The sweep jet actuators appear to be less constrained by spatial integration issues and more limited by the characteristics of the air source that powers them. While there will still be potential space conflicts along certain parts of the span (e.g. near rudder actuators), they are not anticipated to be as severe as those with synthetic jets. This is particularly true for configurations with higher C_{μ} capability, as higher C_{μ} 's require larger (or more numerous) synthetic jet actuators whereas sweep jet C_{μ} can also be elevated by increasing input pressure.

The pressurized air source for the sweep jet system is assumed to come from the APU. In this case, the APU was assumed to have pressurized air capability similar to many current airplanes in this size class. It should be noted that newer airplanes are moving toward system architectures more dependent on electrical power and less so on pressurized air. As a result, the APU on some new airplanes has little or no bleed air capability. In order to install a sweep jet system on an airplane architected in this way, either APU bleed air capability would need to be added, a separate source of compressed air would have to be incorporated, or bleed air from the main engines would have to be plumbed back to the vertical tail. All three options would result in significant cost and weight gains. The last option would also impact performance, as extracting bleed from the one remaining engine on takeoff would reduce the available thrust. Regardless of the source, it is anticipated that the air will be hot at the source, too hot to be routed through composite structure or blown across a composite rudder, both typical of newer airplanes. Therefore, for this study, an air-to-air cooler is employed to reduce the temperature of the air exiting the APU before it is routed into the tail.

Similar to the synthetic jet system, a range of assumptions have been made regarding the estimated weight impacts of sweep jet system incorporation. The incremental weight of the fin is assumed to be identical to that with synthetic jet system. Weight estimates for the sweep jet system hardware are a function of some simplistic assumptions. Their accuracy likely decreases with increasing system size.

The control system and associated LRU's responsible for managing the operation of the actuators valves and other system components is considered to be relatively straightforward in design.

8.2. Conclusions

Both synthetic jet and sweep jet AFC systems have shown promise to be able to provide benefits that exceed their integration and operational costs according to the NPV analysis conducted as part of this study. However, the numbers are based on numerous assumptions, many of which are quite subjective in nature. Therefore, it's important to look beyond the numbers, as they don't capture all of the elements that would factor into a decision as to whether to incorporate either variant of this technology on an airplane program.

Many of the assumptions made and issues identified in this study were explored in the previous section. The primary tasks that must be completed in order to advance either system to be considered for implementation on an airplane can be distilled from this discussion.

The key tasks to be completed in support of a synthetic jet AFC system are:

- Gain an understanding of the required system output at flight scale.
- Mature the actuator technology to produce the required output from flight scale devices with an emphasis on minimizing volume as well as power requirements.
- Determine whether a spatial integration solution can be found with flight scale actuators in the vertical tail of the target airplane.
- Ensure that adequate power is available to drive the actuators in the target application.
- Demonstrate airplane-level robustness of the actuators.
- Update NPV assessment and determine whether system implementation makes sense in light of other options.

The key tasks to be completed in support of a sweep jet AFC system are:

- Gain an understanding of the required system output at flight scale.
- Determine combinations of input pressure and mass flow that would provide required effectiveness.
- If the target airplane application does not have sufficient APU bleed air capability, determine how air requirements can best be met (APU modifications, compressor, engine bleed).
- Update NPV assessment as required and determine whether system implementation makes sense in light of other options.

The first item on both lists is to establish the actuation requirements for a full scale system. It remains to be seen whether knowledge gained at smaller scales regarding C_{μ} , C_b , actuator spacing, and actuator design can be effectively applied at full scale. It is clear that conducting such investigations at large scale with synthetic jets would be difficult in the near term due to lack of maturity of flight scale actuators. However, such investigations are possible now with sweep jet actuators. It is also highly likely that scaling information gleaned from testing of sweep jets at larger scales could be applied to the synthetic jet scenario.

Once this first step is complete, a more focused discussion can commence for both actuation systems. For the sweep jet application, if the required solution falls within the parameter ranges explored in this study, one could quickly derive a more concise NPV answer from the data herein, assuming that the available APU could provide the necessary airflow. If the required actuation is greater than the ranges explored in this study, it appears unlikely that sufficient net benefit will be derived from the system.

If the actuation requirements look favorable, but the available APU is unable to provide the necessary air, alternate sources would have to be explored and their impact assessed in a new NPV. This diminished value could then be weighed against the NPV assessments of alternate AFC implementations and the baseline to determine the best course of action.

While the path forward for sweep jets appears to be fairly straightforward, the path for synthetic jets is less clear. Pneumatic devices of a range of sizes are available today whereas availability of larger synthetic jet devices is far more limited. In addition, there are multiple ways of combining and packaging the synthetic jets, each with its own impact on output characteristics and efficiency,

making predictions about volume and power requirements of larger output systems difficult to formulate. The simplistic scaling done for this study indicates that while there are likely synthetic jet configurations with sufficient authority that can be integrated for this application, it is likely that this integration will be challenging due to device size and a large total power demand.

One conclusion that can be drawn is that much additional work is required to mature “flight-sized” synthetic jets actuators. Packaging and power consumption should be key elements of this work. It is also clear that an accurate assessment of the true integrated impact of a system utilizing these actuators will not be possible until that work is done. It is possible that the desirability of such a system could vary dramatically depending on the outcome of such a development effort. It is for this reason that the next steps listed above for synthetic jet systems include a reexamination of the spatial integration and power consumption aspects of new approaches that may come from such an effort.

In summary, a sweep jet AFC system would appear to be a positive addition to new airplane *if* the required levels of actuation estimated in this study can be validated, and *if* the APU of the target airplane is capable of providing sufficient air to the system. There are presently too many unknowns to confidently make such a statement regarding a synthetic jet AFC system. However, this study has not identified any show stoppers for this approach. Moreover, it has indicated that a positive NPV outcome appears to be possible with the assumptions made in this study. Further synthetic jet actuator development work is required before a more definitive outcome can be predicted for a system that utilizes them.

9. Recommendations for Future Development Activities

It is recommended that both synthetic jet and sweep jet AFC systems continue to be pursued for potential application to commercial airplane vertical tails. While sweep jet actuators are certainly at a higher level of technology readiness than synthetic jets, they rely on having a suitable air source available to power them. In older aircraft, the APU would appear to provide such a source. However, with the current trend in airplane development toward a decrease in reliance on bleed air, this source may no longer be available. A replacement would need to be developed, and it would definitely degrade the net benefit of such an AFC system. Further work is required to quantify the airplane costs of this replacement.

In spite of the unknowns associated with synthetic jet actuators, they still show promise to add value to an airplane in a vertical tail application, and their use of electric power as opposed to pneumatic puts them in better alignment with the systems architecture of future airplanes. However, additional actuator development work is required in order to realize this promise.

For both types of actuation, a deeper understanding of the flow physics associated with the devices and how their effectiveness scales to a flight article is required. The following is a list of suggested future actions:

- Validate flight scale actuation requirements
 - Utilize large scale wind tunnel and/or flight testing
 - Augment testing with CFD
 - Begin with sweep jets
 - Follow up with synthetic jets when available (if still thought to be viable)
- Continue synthetic jet actuator work, focusing on the following areas:

- Maximizing output
- Minimizing space requirements
- Minimizing power requirements
- Maximizing (and demonstrating) actuator robustness
- Developing means of device health monitoring
- Determine preferred airplane source of air for sweep jet system when APU bleed not available
 - Identify options
 - Assess airplane level impacts for all to determine the best approach

Many of the integration issues found in this report are addressed at high-level using limitations on the electric or pneumatic power sources and spatial constraints that are simple, but thought to be conservative. The detailed challenges that could be faced when integrating such systems onto real airplanes are best discovered in the detailed design process. Accordingly, the AFC systems would benefit greatly from efforts to test the systems in-flight, implemented in a vertical tail, using power available to the aircraft systems. Such an effort would mature the technology for future applications.

10. Appendix

10.1. Sensitivities to Duty Cycle – Synthetic Jet System Properties

The effects of applying duty cycle are provided in the plots below, which show synthetic jet AFC system power and weight for application of a 40% duty cycle. The data provided in Section 0 assumes application of a 70% duty cycle for power reduction. Only power and weight are shown, as the other system properties evaluated in the trade studies (jet velocity and actuator geometry) are unchanged.

The primary effect is on the power required, illustrated in Figure 39. The power required is directly proportional to the duty cycle. Accordingly, the most significant contribution that duty cycle application can make is to lower the power required to ensure the system demands are within the available power. Using the APU, supplying up to 450 kW, resulted an AFC system unconstrained by the available power – geometric constraints were the primary constraints on the resulting system. However, the reduced range of power shown below (40 kW to 160 kW) greatly increases the potential to power the synthetic jet system from an alternate power source, reducing the downsides of the assumed AFC system architecture (APU fuel burn, APU maintenance, and reliability).

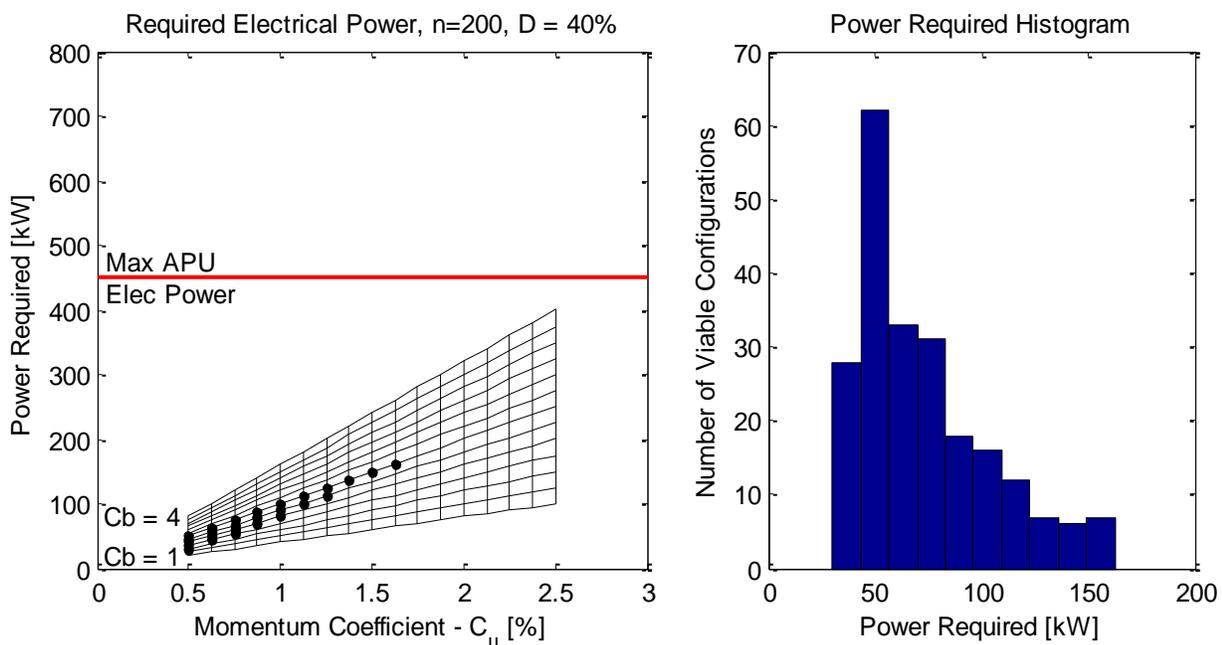


Figure 39: Synthetic Jet AFC System Power Requirements - 40% Duty Cycle

A secondary effect is on the total system weight, shown in Figure 40. The differences shown here, when compared to the system with a 70% duty cycle (Figure 20), are small – on the order of 100 lbs or less. This is a result of the overall system weight being dominated by the actuator weight, which is unchanged with the application of the duty cycle. The weight savings comes from the power distribution weight, which was estimated at 0.6 lbs/kW (see Section 6.1).

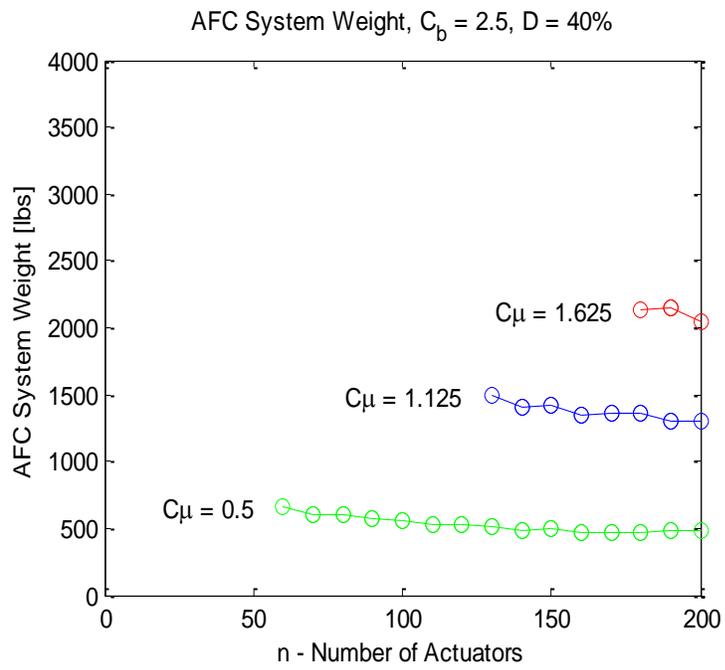


Figure 40: Synthetic Jet AFC System Weight - 40% Duty Cycle

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