

Quiet Ultra-Efficient Integrated Aircraft Using Co-Flow Jet Flow Control

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Abstract

This paper presents the design of a new concept next generation airplane to achieve a significant performance advancement by reducing noise/emission pollution and fuel consumption and increasing the airport capacity and safety at the same time to satisfy future environmental and flight requirements. The new concept airplane includes the following novel design features:

1) The airplane is a flying wing system with tightly integrated propulsion-airframe-flow control and engines buried in the rear part of the airframe; 2) The airplane is formed mostly by the high performance co-flow jet (CFJ) flow control airfoil; 3) The injection jet of the CFJ is introduced from the bypass of the engines after the fan stages. The air inlet of the engines is also the CFJ suction slot, which is spread across most of the wing span to energize boundary layer; 4) The airplane is designed with the projected low specific fuel consumption of futuristic engines and high strength/low weight futuristic materials.

These novel design features may lead to the following superior aircraft performance: 1) High cruise aerodynamic efficiency(L/D), which will significantly reduce fuel consumption and hence emission pollution. 2) Low noise level because: a) The CFJ enhances the lift without using any flaps or slats typical of a conventional high lift system.; b) The short takeoff and landing distance due to high maximum lift reduces the noise footprint. 3) The engines inlet suction and nozzle exhaust jet of the integrated propulsion system enhances the airframe performance by augmenting boundary layer suction and removing the nacelle drag of conventional engines. 4) The airplane is tailless since the yaw control is implemented by varying the thrust on the two sides of the flying wing system. The pitching and rolling moment is controlled by flaps at the rear part of the wing.

To demonstrate the potential superior performance of the new concept airplane, two conceptual designs of the subsonic transports were made, one with the same mission of Boeing 787-8 and the other with the same mission of the N+2 airplane SAX for comparison. The preliminary mission analysis indicates that the fuel consumption, take off weight, and airplane size of the new concept airplane may be significantly reduced in comparison with the current technology.

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1 Introduction

With the projected substantial increase of air traffic in next 20 years, the air transportation system needs a drastic advancement to satisfy future environment demands for reducing emission and noise, airport capacity, and reliability of operation to minimize flight interruption due to severe weather conditions. The JPDO (Joint Planning and Development Office) outlined the concept of the next generation (NextGen) air transportation system in ref [0].

To mitigate the environment pollution, the NextGen airplane needs to have high aerodynamic efficiency with low fuel burn to reduce emission, low noise level for residents around airports, short take-off/landing distance to increase airport capacity and limit the noise footprint, high operability or stall margin to handle severe weather conditions.

The current transport airplane configuration with the fuselage tube and inserted wings has been used since World War II. Until very recently the more efficient flying wing and blended wing body concepts have been explored for civil transport, for example, the Silent Aircraft eXperimental (SAX) being designed in a joint effort by Cambridge University and Massachusetts Institute of Technology [1], and the X-48 blended wing body configuration designed and being tested by Boeing and NASA [2]. Both these airplanes have similar technology and the difference is in the refinement and is evolutionary.

Flow control is a promising technology to break through the conventional aerodynamic constraints and achieve revolutionary performance advancement [3-9]. So far, few existing airplanes use flow control technology. Even the N+2 generation airplanes using blended wing body or flying wing configurations still mostly rely on optimizing geometry shapes without flow control. The conventional heavy high lift system used only for take-off and landing still needs to be carried for the whole flight mission, which is very inefficient.

This paper has designed a novel flying wing airplane system employing co-flow jet (CFJ) flow control airfoil and tightly integrated airframe-propulsion system. The new concept airplane will fly the whole mission using the same configuration with no moving parts of the conventional high lift system. The preliminary mission analysis indicates that the new concept airplane may significantly reduce fuel consumption and emission pollution, decrease noise level at take-off and landing, have extremely short take-off and landing performance, and have high safety margin. The new concept airplane is named as “Quiet Ultra-Efficient Integrated Aircraft” (QUEIA).

1.1 Limiting Factors of Current Technology

To break through the conventional technology, we need to understand first what are the critical factors limiting the performance of the current airplanes.

The Factors for High Fuel Consumption: The “over weight” is one of the critical problems for high fuel consumption. The “over weight” means that the initial take-off weight of an airplane is substantially greater than the payload. We introduce the **Ratio** of the **Pay load** to the maximum take-off **Weight** (RPW) as the measure of merit for this problem. The larger the RPW, the more fuel efficient the system is, and the less fuel burn and emission will be generated.

The following numbers give an idea of the current technology: The Boeing 737-800 with the payload of 45188 lbs and range of 3060nms has the RPW equal to 25%. With the range increased, such ratio will be decreased exponentially. For Boeing 787-8 with about the same payload and twice the range, the RPW is only 9.7%. That is, the payload of B787-8 only takes less than 10% of the total weight at take off.

There are three main factors contributing to the current RPW limits: 1) The low aerodynamic efficiency represented by the ratio of lift to drag (L/D), which requires an airplane to carry a large amount of fuel; 2) The heavy mechanical system for the high lift system, which is only used at take off and landing, but need to be carried for the whole mission. 3) The large wing surface area to have sufficiently low wing loading at take off to minimize take-off/landing distance. Such large wing surface area is not needed at cruise and will result in increased structure weight for the whole mission.

The Factors for High Noise: The high noise level of a current airplane is attributed to the following factors: 1) the nozzle jet noise at take off; 2) the fan noise at take-off; 3) the noise from the high lift system composed of flaps and slats at landing; 4) the wake noise of the airplane at take off and landing; 5) the long take-off/landing distance and shallow climb/descend angles; 6) the landing gear noise at landing.

The objective of this paper is to design a new concept next generation airplane that may overcome the above limiting factors of the current airplanes, reduce emission/noise and increase the airport capacity.

2 Co-Flow Jet Airfoil Concept

To better understand the advantages of QUEIA which incorporates the CFJ flow control airfoil, we will have a brief overview of flow control and then introduce the CFJ airfoil concept in the following section.

2.1 Overview of Flow Control

When a flow control technique is developed, three primary issues need to be considered: 1) effectiveness to enhance lift, stall margin and drag reduction, 2) energy efficiency to minimize penalty to propulsion system or weight increase, and 3) ease of implementation.

Circulation control (CC) [25,26] airfoil is one of the flow control techniques that has been pursued for aircraft performance improvement in the last three decades. A CC airfoil relies on the Coanda effect that requires a large airfoil leading edge (LE) and trailing edge (TE). However, the large LE and TE may create large drag at cruise conditions. To overcome the dependence on a blunt TE, a movable flap at the airfoil TE has been suggested by Englar [27]. Consequently, such moving parts impose a weight penalty. At large angles of attack (AoA), if only a TE blowing is used, a CC airfoil may stall at a smaller AoA than a non-controlled airfoil [28]. To maintain sufficient stall margin, a LE blowing is also needed.

A considerable penalty of CC airfoil is the dumped blowing jet mass flow, which is imposed on the propulsion system. Usually, an engine will incur a 1% thrust decrease for a 1% bleed flow and will result in a 1-3% fuel consumption increase depending on whether the bleed is from the compressor front or back stage. Furthermore, for a CC airfoil, the drag measured in the wind tunnel is not the actual drag occurring on the aircraft. This is because, in a wind tunnel test, the penalty to draw the mass flow from the freestream as the supply for the jet injection is not included in the drag measurement. The actual drag, also called the "equivalent" drag, needs to include this penalty [13], which is composed of the ram drag and captured area drag. The equivalent drag of a CC airfoil could be significantly larger than the drag measured in the wind tunnel. To reduce the penalty associated with CC airfoil due to the dumped jet mass flow, Jones[29] used a pulsed jet and was able to substantially reduce the jet mass flow rate.

Recently, other new technology using zero-net mass flux (ZNMF) synthetic jets [30] and dielectric-barrier discharge plasma actuators [31, 32] have been developed. These approaches avoid dumping the jet mass flow. However, at present, both ZNMF and plasma actuators are generally lacking in terms of sufficient actuator authority for high speed flows.

Recently, a zero-net mass-flux jets flow control airfoil, co-flow jet airfoil, has been developed by Zha et al. [10-13] to avoid dumping the jet mass flow and achieve the performance enhancement without relying on Coanda effect.

2.2 The Co-Flow Jet Airfoil

In the Co-Flow Jet Airfoil concept [10-13], an injection slot near leading edge and a suction slot near trailing edge on the airfoil suction surface are introduced as sketched in Fig. 1. A high energy jet is injected near the leading edge in the same direction of the main flow and the same amount of mass flow is drawn near trailing edge. The jet is hence maintained as zero-net mass flux flow control. The fundamental mechanism is that the severe adverse pressure gradient on the suction surface strongly augments the turbulent shear layer mixing and diffusion between the main flow and the jet. The mixing then creates the lateral transport of energy from the jet to the main flow and allows the main flow to overcome the large adverse pressure gradient and remain attached even at very high angles of attack. The stall margin is hence significantly increased. At the same time, the high momentum jet drastically increases the circulation, which significantly augments lift, reduces drag or even generates thrust (net negative drag). Fig. 2 shows a typical comparison where the baseline airfoil has a massive separation at high angle of attack, whereas the CFJ airfoil has a very well attached flow [10,11]. To most effectively make use of the adverse pressure gradient to enhance mixing, the injection slot must be located downstream of the leading edge suction peak, where the pressure is the minimum of the flow field. The injection near LE at a low pressure location and the suction near TE at a high pressure location create a mechanism to minimize the CFJ pumping energy expenditure.

In addition to the lift and stall margin increase, a corresponding special feature of the CFJ airfoil is its super-suction at the LE. Due to the very high circulation, the LE suction is so strong that the low pressure at the leading edge results in a thrust at low AoA. That is, the airfoil generates both lift and thrust (not drag) at low AoA. This has the similar effect of a flapping wing, in which lift and thrust are produced simultaneously due to LE super-suction. When the wing generates thrust or reduces drag, the required thrust from engines is reduced, or an airplane may fly forward just relying on the CFJ with no conventional engines [14].

Fig. 3 shows the measured lift coefficients for the baseline uncontrolled NACA 0025 airfoil and CFJ airfoil in proof-of-concept wind tunnel tests[11,12]. The $C_{L_{max}}$ is increased from 1.52 to 5.02, a 3.2 times increase. The stall AoA is increased from 19° to 44° . Fig. 4 is the drag polar of the CFJ airfoil with a larger (2x) injection slot size than the airfoil tested in Fig. 3. Fig. 4 shows that the drag of the CFJ airfoil is significantly reduced compared with the baseline uncontrolled airfoil. For the case with an injection total pressure coefficient of 1.24, the drag actually becomes negative and represents thrust. The range over which thrust is available is rather large. With $C_\mu=0.1$, a 113% increase of maximum lift and a reduction of 67% of minimum drag are obtained[11,12].

Note that a CFJ airfoil is a zero-net mass-flux flow control airfoil. Therefore, the momentum coefficient for the CFJ airfoil does not represent the same energy expenditure as a CC airfoil. The energy expenditure of the CFJ airfoil is lower[13]. In addition, the research so far [10-13] has been at the level of proof-of-concept study without optimization. With continuous efforts on CFJ airfoil research, the effective C_μ is expected to be significantly reduced similar to the development history of CC airfoil.

In [13], the control volume analysis indicates that the drag or thrust of a CFJ airfoil measured in the wind tunnel is the actual force acting on the airfoil in the stream-wise direction. There is no extra drag that needs to be added. This is not the same as the CC airfoil, which must consider the equivalent drag due to the suction penalty from the free-stream. Comparing the CC airfoil and CFJ airfoil, both have blowing and hence both need suction due to mass conservation. The difference is that the CFJ airfoil has the suction on the airfoil suction surface near trailing edge, which will enhance the airfoil performance. Whereas the CC

airfoil has the suction from freestream, which does not directly interact with the airfoil, but introduces the ram drag and captured area drag.

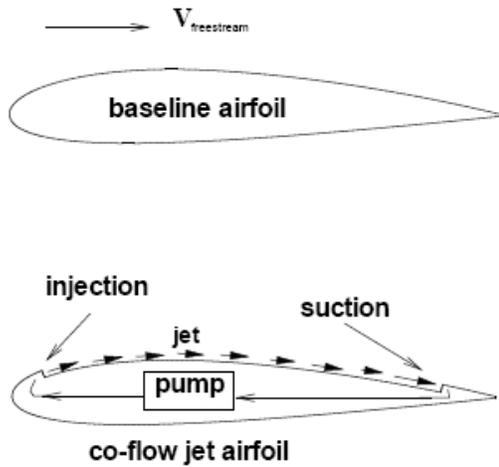


Figure 1 – Baseline Schematic for CFJ Airfoil Showing Pump Concept

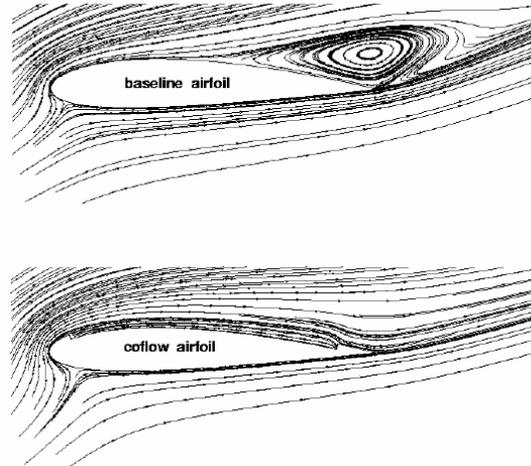


Figure 2 – Flow Field for baseline NACA 2415 and CFJ Airfoil at High AoA

2.3 Application of CFJ Airfoil

An airfoil is the most fundamental element of an airplane. The CFJ airfoil achieves three effects simultaneously: lift augmentation, stall margin increase, and drag reduction [10-13]. The advent of CFJ airfoil hence may bring a new design philosophy for future airplane performance.

The feature of generated thrust enables a novel approach for commercial aircraft noise reduction. For example, similar to the use of a high-bypass fan, a CFJ airfoil aircraft may potentially produce low noise at takeoff due to the lower thrust (and, hence, lower nozzle exhaust velocity) requirement. Note that jet noise scales with the 8th power of the nozzle exhaust velocity and is the primary noise source at takeoff. The wing thrust or drag reduction of the CFJ airfoil can be used as another avenue to redistribute the thrust of the aircraft to reduce the nozzle exhaust jet velocity. At the same time, the extremely high lift generated by a CFJ wing is ideal for ESTOL (extremely short takeoff/landing) aircraft. During approach, the CFJ airfoil can generate very high lift without using a flap system, thus reducing the noise level. The high lift will allow low take off and landing speed, and thus low noise due to airplane wake.

In general, the CFJ aircraft can reduce noise by both increasing the distance of the noise sources from ground and by reducing the amplitude of the noise sources. Although the co-flow jet injection mixing may generate turbulent mixing noise, the negative effect is expected to be minimal because the injection is on the upper surface of the wing near the leading edge. The noise radiation directivity will likely be primarily in the upward direction and will not have a large impact on the ground.

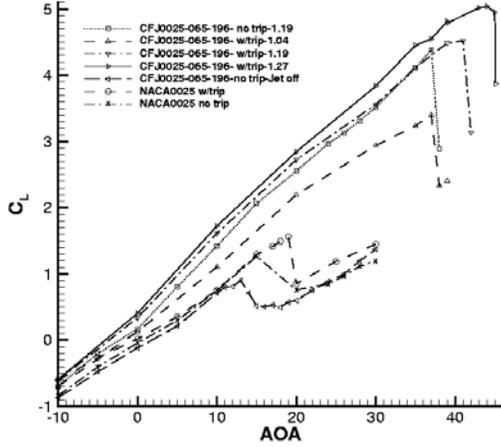


Figure 3 – Measured lift vs angle of attack for NACA 0025 and CFJ0025-065-196 airfoil

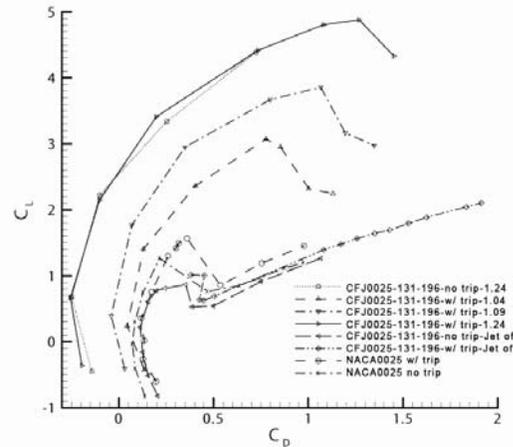


Figure 4 -- Measured drag polar for NACA 0025 and CFJ0025-131-196 airfoil

The CFJ airfoil could be used for the whole flight mission instead of only for takeoff and landing [10]. For different phase of the flight envelope, the lift and drag (or thrust) of the CFJ wing can be controlled by the strength of the jet. For example, during takeoff, a strong jet is needed to generate large lift and low drag. During cruise, a very weak jet is sufficient to provide the necessary lift and drag reduction. During approach, the CFJ can generate high lift and high drag at high AoA. The CFJ wing may also potentially remove the mechanical control surfaces for roll, yaw, and longitudinal control by generating different lift, drag, and moments on the controlled wing.

Even though CFJ can enhance airfoil performance, it will have certain energy expenditure, which is the power required to pump the CFJ. The power consumed by the CFJ pump alone may be expressed as [10, 13]:

$$P_{pump} = \frac{\dot{m} C_p T_{o1}}{\eta} \left(\left[\frac{p_{o1}}{p_{o2}} \right]^{\frac{\gamma-1}{\gamma}} - 1 \right) \quad (1)$$

Where, \dot{m} is the CFJ mass flow rate, T_{o1} and p_{o1} are the total temperature and total pressure, respectively. The subscript 1 and 2 stand for the injection and suction. C_p is the specific heat capacity at constant pressure, γ is the ratio of specific heats, and η is the pumping efficiency. Based on Equation 1, the power required to pump the jet is dependent on the ratio of the total pressure at the injection and suction and the mass flow rate of the jet. The CFJ mass flow rate is usually significantly smaller than the engine mass flow rate.

The ratio of lift to drag L/D is the measure of the cruise aerodynamic efficiency of an aircraft. To consider the energy consumption due to CFJ pumping power, we define a total drag that includes the aerodynamic drag and the equivalent drag converted by the power consumption of the CFJ:

$$D_{total} = \frac{DV_{\infty} + P_{pump}}{V_{\infty}} \quad (2)$$

The overall L/D then will be

$$\left(\frac{L}{D}\right)_{total} = \frac{LV_{\infty}}{DV_{\infty} + P_{pump}} \quad (3)$$

Eq. (3) reflects the equivalent lift to drag ratio that includes the pumping power requirement for the CFJ flow control. From Fig. 3 and 4 of the wind tunnel tests, we know that when a CFJ is acting on the airfoil, it increases lift and at the same time also reduce drag. Eq. (3) means that even though the power consumed by CFJ is equivalent to adding drag to the aircraft system, it reduces the aerodynamic drag (D) and increases lift (L) at the same time. As a lump effect, the overall $(L/D)_{total}$ could be increased. This is the basis to achieve high aerodynamic efficiency by using CFJ airfoil flow control. Usually the pumping power is from the aircraft engines. Hence the CFJ airfoil brings a mechanism to convert a part of thrust to the increase of L/D. The more we can convert thrust to increase L/D, the more efficient of the flying system.

In summary, the CFJ airfoil may not only improve the airplane performance at take-off and landing, but may also improve the cruise efficiency. As indicated by Kuchemann [22], the most efficient aircraft performance is achieved by having one type of flow throughout the complete flight mission. The CFJ wing may achieve this goal. The proposed QUEIA configuration is the first step to apply a CFJ airfoil to a realistic airplane.

3 The New Concept Airplane, QUEIA

3.1 The Future Scenario

To define the future scenario, the Boeing 787-8 is used as the reference airplane of the current technology. The Boeing 787-8 is a long-range transport with the payload of 47040 lbs and range of 7650nm. The proposed airplane with the same mission as Boeing-787-8 in the time frame of 2030-2035 will achieve the following performance improvement:

1. Increase the ratio of payload to the maximum take-off weight (RPW) by 50% or more to reduce the airplane weight.
2. Reduce fuel burn for the whole mission by 70% or more.
3. Reduce the Landing/Take-Off (LTO) NO_x by 70% or more.
4. Keep the 55 db LDN (Day-Night average sound Level in decibels) for all airports including those for general aviation (GA).
5. Achieve STOL performance to increase airport capacity including the ability to use GA airports. Specifically, the take-off/landing distance should be less than 3000ft

3.2 Design Strategy

QUEIA design is the first rigorous effort to apply the CFJ airfoil to an airplane with realistic mission of future scenarios. Even though the CFJ airfoil appears to have superior performance, applying it to an airplane system is unprecedented and not straightforward. We take the two most recent designs, Boeing 787-8 and the N+2 airplane SAX [1], as the reference mission requirements. Only a design based on realistic missions can examine if the concept is feasible.

The first idea in mind when QUEIA was designed was that the airplane must be a flying wing so that the CFJ airfoil can cover most of the wing surface to make maximum use of the CFJ benefit. The second idea

was that there must be an efficient CFJ pumping system. The aircraft engines act as an ideal pumping system with high pressure air in the fan/compressor and low pressure at the engine inlets. The CFJ airfoil concept is based on zero-net mass-flux flow control. The pumped air for injection must return to the pumping source by the suction. If the engines are hung externally like the conventional airplane configuration, it is difficult to return the sucked air to the engines. It is also awkward and inefficient to introduce the high pressure air from the engines hung outside of the airframe.

The third idea then came out that the engine inlet and the CFJ airfoil suction slot may be combined as one structure. All the air mass flow drawn from the suction slot will enter the engines. A small part of the high pressure air after the high bypass fan stage will be introduced to the wing leading edge to be used for CFJ injection jet. The fourth idea was that burying the engines behind the suction slot in the rear part of the airplane appears to be the most efficient option to accommodate the CFJ suction since there is no turning for the flow drawn in. To do so, we have to replace a conventional large size engine by multiple smaller engines.

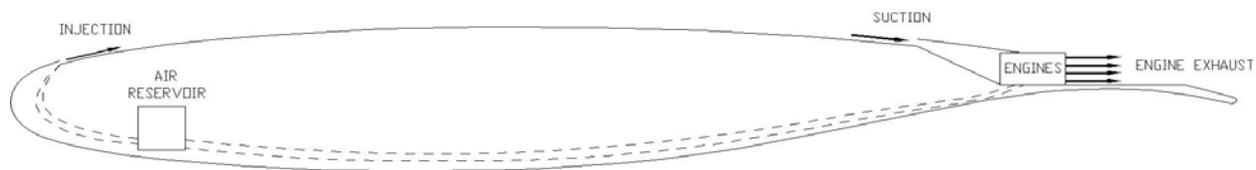


Figure 5 – 2D Drawing of Supercritical Airfoil for QUEIA showing CFJ Slots and Basic Ducting

Figure 5 shows the design philosophy and working principle of this new flying wing concept using the co-flow jet airfoil. The CFJ airfoil is modified from the baseline supercritical NACA SC₂-0714 airfoil. The suction slot near the trailing edge is also the inlet of the propulsion system and the CFJ. Most of the mass flow will go through the engines and exhaust to ambient to generate the momentum for thrust. A small portion of the high pressure air induced from the bypass after the fan stage will be used as the injection jet near the leading edge of the CFJ. When the same amount of mass flow is drawn into the inlet or the suction slot, the mass flow is energized and the engines hence need to do less work compared to draw the flow from ambient. We also need to point out that the injection pressure can be easily obtained from the high bypass fan since the injection location is at the minimum pressure location of the airplane. If the injection total pressure is two times higher than the local pressure, the jet will reach sonic speed, which is usually more than needed.

Figure 6 displays the 3D external flying wing configuration of QUEIA designed with a similar mission to the Boeing 787-8 with cruise Mach number of 0.82, 50000 lb payload for 205 passengers, and 5000 nm range. Note the buried propulsion system composed of six engines in the rear of the airframe. The high performance CFJ airfoil encompasses 70% of the flying wing as shown by the blue color in Figure 6. The CFJ suction slot serves as the only air intake for the engines. The maximum thrust required is about 60000 lbs, which can be achieved by two CFM-56 class engines. However, instead of using two large CFM-56 class engines, we propose to use six smaller PW800 gear fan engines that generate about the same thrust and can be buried in the airframe as an integrated part of the CFJ and airframe-propulsion system.

The buried engines are not only more efficient for



Fig. 6 The top view of QUEIA with integrated airframe-propulsion and CFJ wing cruising at Mach 0.85.

pumping CFJ, but also remove the nacelle drag. In addition, the engine inlet suction and exhaust jets become a part of the flying wing flow and have favorable effect to energize the boundary layer on suction surface. At the same time, the engines buried on the upper surface of the flying wing have the shield effect to direct the nozzle jet mixing noise radiating upper-ward to mitigate noise pollution to the residents on ground. The large amount of cold airflow from the high bypass duct will surround the hot high temperature nozzle jet and protect the airframe body from being heated. Some high temperature resistant material can be also used locally in the exhaust region.

The tightly integrated airframe and engine system is very different from the current airplane technology, for which the only role that engines play is to generate thrust and have little interaction with the airframe, except that the pylons will negatively affect the wing performance and the nacelles will increase drag.

3.3 Design Tool Used

The mission and component design is based on the code given by Corke in [15], which provides a first order design deck using empirical data and correlations. The design code is modified to include the CFJ airfoil effect as indicated from Eq. (1-3). The CFJ airfoil experimental results [11-12] and some 2D CFD simulation is input to provide partial airfoil characteristics. The $C_{\mu}=0.0008$ is used for the CFJ at cruise and $C_{\mu}=0.08$ is used at take-off. Since the QUEIA flow field with jet interaction is very 3-dimensional, the results of this preliminary mission analysis and design hence may be more qualitative than quantitative. More accurate quantitative analysis will rely on wind tunnel tests and 3D CFD simulation. The QUEIA concept may apply to any flying wing or blended wing configuration. In our design, we use a platform similar to that of the SAX [1] with the aspect ratio slightly larger. This is to ensure the safety that the airplane can glide in case all the engines fail to operate.

3.4 The Configuration

Fig. 7 shows the same CFJ airfoil as Fig. 5 used in the region with no engines such as on the wing. The slots location and size are designed based on the experience from the subsonic CFJ airfoil studied in [10-13] with no optimization. Some 2D CFD simulation is conducted to verify that the slots can pass the maximum mass flow rate at $C_{\mu}=0.1$. The injection slot has a height of 0.2% of the local chord and is placed at the 4.1% chord location. The suction slot is placed at the 71% chord point, and it has a height of 0.68% of the local chord.

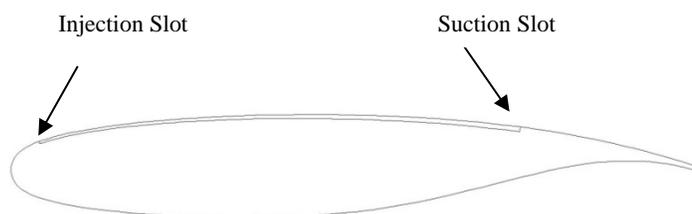


Figure 7 – NACA SC₂-0714 Baseline shown with CFJ Modifications

Figure 8 shows the orthographic projections of the QUEIA. The wingspan is 166.3 feet and its center chord measures 112.7 feet. In blue is the area covered by the CFJ which is spread across most of the wing span. The suction slot area is 5% larger than the summation of the six PS800 engine inlets to account for some inlet blockage. It is interesting to note that the QUEIA has plenty of volume to accommodate all the needs including fuel storage, luggage, and the ducting for the CFJ injection. Each passenger can enjoy the space of a first class seat. This is attributed to the large volume of QUEIA’s flying wing configuration and the smaller amount of fuel to carry due to the high ratio of L/D.

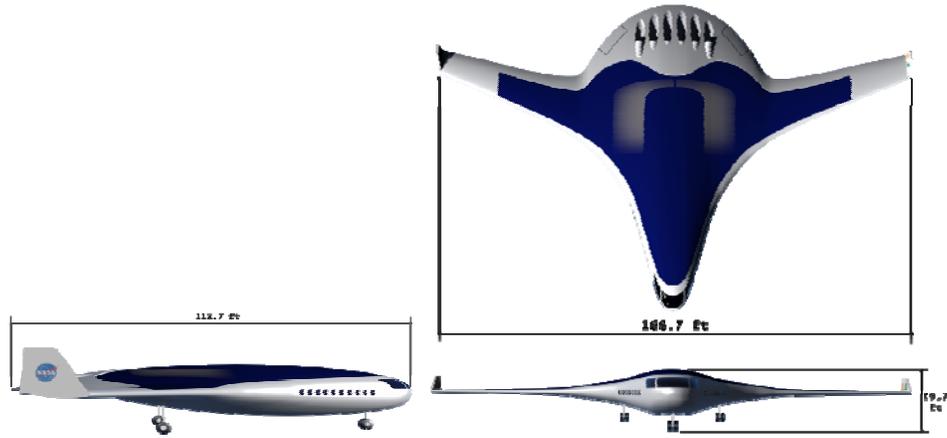


Figure 8 – Orthographic Views of QUEIA

3.5 Stability and Control

QUEIA is tailless. Since three engines are placed on each side of the aircraft centerline, asymmetric thrust generated by the engines and CFJ will cause the aircraft to yaw. The control feedback system must be looped with the propulsion system to control the amount of yaw needed to return the aircraft to coordinated flight at any instant but allow a constant lift force from the CFJ. There will be a split elevator (or aileron pair), as shown in **Figure 8**, located behind the engines that will cause the pitching moments and rolling about the longitudinal axis of the airplane. These control surfaces will be the only moving parts (excluding the landing gear) that QUEIA will use.

3.6 QUEIA Performance

Table 1 shows the comparison of QUEIA’s performance with other airplanes with the same mission requirements including payload, range, cruise Mach number, and flight altitude to demonstrate its potentially superior performance. Two reference airplanes are used for comparison, one is the Boeing 787-8 which is considered as the current technology, and the other is SAX[1] which is considered as the N+2 airplane. Column 3 and 4 are the Boeing 787-8 mission performance calculated using our design deck compared with the published data. This is to validate that the design deck we used is acceptable. The fuel weight, total take-off weight, and take-off/landing distance all agree fairly well with the published data. Column 6 is the Boeing 787-8 designed with the projected benefit of lower material weight and engine fuel consumption by year 2030, which are also used by the QUEIA-2030 given in column 5. The projected fuel consumption reduction by 2030 used is 25% lower than current technology. The projected structure material weight reduction by 2030 is 5%. We assume 1% additional weight reduction for QUEIA due to no high lifting system. The comparison of column 5 and 6 hence will indicate the difference solely due to the different aerodynamic design concepts and configuration.

The overall required power to pump CFJ is small. For QUEIA at cruise, the $C\mu=0.0008$ is used and the CFJ mass flow rate is 9.7% of the engine mass flow. At takeoff, the $C\mu=0.08$ is used and the CFJ mass flow rate is 16.9% of the engine flow rate. The total pressure ratio used to pump CFJ was taken as 1.1, which is estimated from the 2D CFD simulation and the wind tunnel experiment. The pumping efficiency is taken as 80% to be conservative.

The L/D is difficult to estimate without using a more sophisticated tool such as CFD and wind tunnel tests. A conservative L/D of 22, which is about 10% higher than the current technology, is used assuming the CFJ has little enhancement during cruise, but the L/D is benefited from the integrated airframe-propulsion system. The low stall Mach number predicted for QUEIA will reduce takeoff and landing distances. Note that QUEIA’s takeoff and landing distances are 2532 and 2437 feet, respectively, which are far shorter than

all other airplanes in the table. The decrease in stall speed will also allow steep climb and descent angles that will aid noise abatement around airports. The short takeoff and landing of QUEIA will allow access to more small airports.

Table 1 – Comparison Chart to other existing and comparable aircraft engine rating given in hp

	1	2	3	4	5	6
Performance	QUEIA 2030	SAX-40	Boeing 787-800 Published	Boeing 787-800 Design Deck	QUEIA 2030	Boeing 787-800 2030
Wingspan (ft)	166.27	207.40	196.8503937	196.85	166.27	196.85
Length (ft)	112.71	144.00	187.007874	187.01	112.71	187.01
Wing Area (ft)	5059.75	8998.00	3501.4	3501.40	5059.75	3501.40
Height (ft)			55.77	55.77		55.77
Max. Takeoff Weight	176041	332560	476000	475993	176041	253951
Max Payload (lbs)	50000	51600	47040	47040	50000	47040
Empty Weight (lbs)	83620	207660	239200	236017	83620	121239
Fuel Weight (lbs)	42422	7331	189760	192936	42422	85675
Structure Weight	0.475	0.625	0.503	0.496	0.475	0.477
Stall Mach No.	0.101	0.145	0.211	0.211	0.101	0.154
Takeoff Mach No.	0.121	0.174	0.254	0.254	0.121	0.185
Cruise Mach	0.820	0.800	0.850	0.850	0.820	0.850
Takeoff Distance (ft)	2532	N/A	9255	9369.38	2532	2887.00
Landing Distance (ft)	2437	N/A	4986	4919.41	2437	3182.52
Range (nm)	5000	5000	7650	7650	5000	7650
Cruise Altitude (ft)	47000	40000	33000	35000	47000	35000
Airfoil Name	SC20714CFJ	SC20714	BAC	NACA 23012	SC20714CFJ	NACA 23012
C _{lmax_2D}	3.27	1.93	1.91	1.91	3.27	1.91
Base Drag, C _{d0}	-0.03448 at takeoff; 0.003 at cruise	0.0070	0.0070	0.0070	-0.03448 at takeoff; 0.003 at cruise	0.0070
Cruise L/D	22	20.10	20.84	20.84	22	20.84
Aspect Ratio	5.46	4.76	10.58	10.58	5.46	10.58
Stall Angle (degrees)	25.37	16.00	16.19	16.19	25.37	16.19
Max Wing Loading	34.8	36.96	136.00	135.94	34.8	72.53
Engine	PW800	N/A	Trent 1000	Trent 1000	PW800	Trent 1000
Number of Engines	6	3	2	2	6	2
Total Thrust (lbf)	52959	290000.0	150000.0	175670.7	52959	149973.9
Bypass ratio	~10	High	~10	~10	~10	~10
Total Mass Flow	1800	N/A	5340.00	6587.33	1800	5339.07
Engine Length	103	N/A	160.00	219.58	103	159.97
Engine Diameter	39.5	N/A	112.00	153.70	39.5	111.98
Engine Weight (lbs)	1725	N/A	11924.00	13815.12	1725	11921.93

Table 2 summarize the performance improvement of QUEIA based on this preliminary mission analysis. Compared with current Boeing 787-8, the RPW of QUEIA is increased by 187% and the fuel consumption and hence emission are reduced by 83%. So the “over weight” problem could be significantly improved. In

theory, all the future scenario requirements described in Section 3.1 are satisfied except the noise reduction is not quantified, but the noise level is expected to be significantly reduced. Compared with the N+2 airplane SAX and the Boeing 787-8 in year 2030, the QUEIA is still substantially lighter, has less fuel burn and emission, and has much shorter take-off/landing distance. It also has far smaller size represented by the foot print area defined as (wing span) x (airplane length), which is about half of the size of Boeing 787-8.

Table 2 Comparison of performance improvement of QUEIA and other airplanes

QUEIA-2030 Improvements	Compared with B-787-8 current	Compared with B-787-8 2030	Compared with SAX
Increase of RPW, %	187.45	53.51	83.22
Take-off weight reduction, %	-63.02	-30.68	-47.06
Fuel consumption reduction, %	-83.31	-62.41	-56.06
Take-off distance reduction, %	-72.64	-12.30	N/A
Landing distance reduction, %	-51.12	-23.43	N/A
Area reduction, %	-49.09	-49.09	-37.25

4 Impacts

4.1 Low Energy Expenditure and Emission

The significantly increased RPW of QUEIA will need much less power and fuel consumption. When some power is consumed to generate the CFJ, the total L/D of a CFJ airplane could be significantly increased. Since the lift coefficient of a CFJ airfoil element is higher than a conventional airfoil, the overall lifting surface area to have the same payload will thus be smaller. The weight of the airplane and the drag due to the wetted surface will be also significantly reduced. The “over weight” problem of a conventional airplane could be substantially improved. With the buried aircraft engines, the drag due to the engine nacelles will be removed. The reduced weight and drag will reduce the energy consumption and emission.

4.2 Short Takeoff/Landing to Increase Airport Capacity

The takeoff/landing distances and the stall velocity are primarily determined by the maximum lift coefficient and wing loading. The CFJ airfoil enhances the maximum lift. The low weight and large wing area of a lift wing configuration decrease the wing loading. QUEIA’s stall velocity thus appears to be significantly lower than a conventional airplane. Consequently, QUEIA could display ESTOL (Extremely Short Takeoff and Landing) performance. The decreased stall velocity will reduce runway distance use, which could multiply an airport capacity and make the general aviation airport usable for this large aircraft.

4.3 Low Noise

The QUEIA design has been created with a number of important features that may reduce the overall noise footprint compared to conventional aircraft. First, a significant reduction in perceived noise will be obtained simply through improvements in the climb and descent performance. Specifically, the ESTOL performance allows steep climb and decent angles of 3.5 and -6 degrees, respectively. The aerodynamic capabilities of the CFJ will ensure that the aircraft climbs more efficiently, and thus will achieve greater altitude at the edge of airport boundaries. The high lift and reduced stalling Mach number will also allow the aircraft to takeoff with lower power, lower thrust, and thus with significantly reduced noise. Similarly, the descent may begin closer to the airport to reduce the noise footprint during landing. The gliding performance

rendered by the large L/D value also provides for a minimum power requirement, thus reducing engine noise during approach to landing.

Airframe noise radiated from the QUEIA aircraft may also be significantly lower compared with conventional aircraft. The CFJ will operate without the use of conventional flap and slat systems that are known to be responsible for a majority of the airframe noise signature. The noise generated by the CFJ system will be a significant focus of the proposed statement of work. It is anticipated that the upward facing surface of the CFJ suction and blowing slots will yield a directivity pattern that yields very low perceived noise levels on the ground. In addition, noise control and abatement strategies such as acoustic liners will be considered in the context of scaled model testing and full scale noise estimates.

Lastly, the large number of proposed engines (6), as well as their placement on the upper surface of the wing/body design will provide significant noise reduction. Specifically, the engines inlet and exit are both placed in locations where direct line-of-site to ground is blocked. In addition, noise control materials can be used in the vicinity of the engine without aerodynamic penalty.

6. Conclusions:

This paper conducted a conceptual design of a new concept airplane QUEIA, which includes the following novel design features:

- 1) The airplane is a flying wing system with tightly integrated propulsion-airframe-flow control and engines buried in the rear part of the airframe;
- 2) The airplane is formed mostly by the high performance co-flow jet (CFJ) flow control airfoil;
- 3) The injection jet of the CFJ is introduced from the bypass of the engines after the fan stages. The air inlet of the engines is also the CFJ suction slot, which is spread across most of the wing span to energize boundary layer;
- 4) The airplane is designed with the projected superior specific fuel consumption of futuristic engines and high strength/low weight futuristic materials.

These novel design features may lead to the following superior aircraft performance: 1) Very high cruise aerodynamic efficiency(L/D), which will significantly reduce fuel consumption and hence emission pollution. 2) Extremely low noise level because: a) The CFJ enhances the lift without using any flaps or slats typical of a conventional high lift system.; b) The short takeoff and landing distance due to high maximum lift reduces the noise footprint. 3) The engines inlet suction and nozzle exhaust jet of the integrated propulsion system enhances the airframe performance by augmenting boundary layer suction and removing the nacelle drag of conventional engines. 4) The airplane is tailless since the yaw control is implemented by varying the thrust on the two sides of the flying wing system. The pitching and rolling moment is controlled by flaps at the rear part of the wing.

To demonstrate the potential superior performance of the new concept airplane, two conceptual designs of the subsonic transports were made, one with the same mission of Boeing 787-8 and the other with the same mission of the N+2 airplane SAX for comparison. The mission analysis indicates that the fuel consumption, take off weight, and airplane size of the new concept airplane may be significantly reduced in comparison with the current technology. However, the mission analysis data are based on approximate inputs and empirical relations, which only have marginal accuracy. More rigorous performance assessment needs to be done by wind tunnel tests and CFD analysis in future.

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