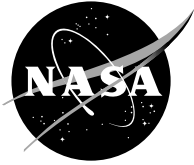


NASA/TM—2003-212696



Embedded Wing Propulsion Conceptual Study

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November 2003

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Prepared for the
Vehicle Propulsion Integration Symposium
sponsored by the NATO Research and Technology Agency
Warsaw, Poland, October 6–9, 2003

National Aeronautics and
Space Administration

Glenn Research Center

November 2003

Acknowledgments

The authors would like to express their thanks to Danny P. Hwang, Daniel N. Kosareo, James R. Davic, and Jeffrey J. Berton, NASA Glenn Research Center and Mark Waters, Georgia Institute of Technology, for their contributions to this paper.

Trade names or manufacturers' names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

The Propulsion and Power Program at NASA Glenn Research Center sponsored this work.

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Embedded Wing Propulsion Conceptual Study

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ABSTRACT

As a part of distributed propulsion work under NASA's Revolutionary Aeropropulsion Concepts or RAC project, a new propulsion-airframe integrated vehicle concept called Embedded Wing Propulsion (EWP) is developed and examined through system and computational fluid dynamics (CFD) studies. The idea behind the concept is to fully integrate a propulsion system within a wing structure so that the aircraft takes full benefits of coupling of wing aerodynamics and the propulsion thrust stream. The objective of this study is to assess the feasibility of the EWP concept applied to large transport aircraft such as the Blended-Wing-Body aircraft. In this paper, some of early analysis and current status of the study are presented. In addition, other current activities of distributed propulsion under the RAC project are briefly discussed.

NOMENCLATURE

F_j	jet force
M	Mach number
M_j	tail-jet Mach number at nozzle exit plane
M_∞	free-stream Mach number
U	axial velocity
U_∞	free-stream axial velocity
c	airfoil chord
c_d	sectional drag coefficient
c_l	sectional lift coefficient
c_p	pressure coefficient
α	angle-of-attack
θ	jet flap angle

BACKGROUND

NASA has been investigating distributed propulsion concepts applied to future aircraft under the Revolutionary Aeropropulsion Concepts or RAC project. The project is primarily directed towards the NASA Aerospace Technology Enterprise Goal "Pioneer Technology Innovation" and also supported by the "Revolutionize Aviation" and "Advance Space Transportation" goals. This paper will address some of the current activity in the area of distributed propulsion under the RAC project looking 20 to 40 years into the future.

Since the introduction of large jet powered transport aircraft such as the Boeing 707, the majority of these vehicles have been designed by placing thrust-generating engines either under the wings or on the fuselage to minimize aerodynamic interactions on the vehicle operation. The exception to this kind of configuration was the British De Havilland Comet aircraft, which was one of the first generation jet transports. Figure 1 shows some early aircrafts with various propulsion system placements. This aircraft had

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all its engines buried in the thick wing root section but really never took advantage of the full benefits of integrating two distinct systems, i.e., the propulsion system and wing. The Comet suffered initially mysterious but now well documented structural fatigue failures of the fuselage that dramatically affected the production. Beyond the fatigue failures, the embedded propulsion system caused maintenance problems because of low reliability of the first generation jet engines of the 1950's. The apparently low drag configuration also caused adverse aerodynamic interactions between engine flow / wing aerodynamics. In spite of these setbacks, a modern version of the Comet continues to fly reconnaissance missions as the BAe Nimrod.

In the late 1960's, a turbofan propulsive wing Vertical/Short Take-off and Landing or V/STOL concept ADAM III¹ was studied for various missions but the design never went into production possibly due to the problem of ducting hot gas through the wing structure. For this concept, the gas generators and their inlets were installed near the wing root to provide hot gas to the turbines that drove high bypass ratio turbofans. The turbofans and turbines were located in the wing away from the gas generators. The hot gases from the gas generators were routed through long ducts across the wing span to the location where the turbines were installed. The inlets and nozzles for the turbofans and turbines were also all within the wing structure away from the gas generators and provided distributed thrust to the vehicle.

Aside from the conventional cylindrical fuselage type vehicles, there were flying wing aircrafts such as the Northrop YB-49 and more recent B-2 bomber for the military that had all the engines buried in the wing. In particular, the YB-49, which was flown in the 1940's, had four linearly arranged engines in each side of wing with subsonic rectangular inlets and conventional circular nozzles at each side of the wing leading edges and trailing edges, respectively. See Fig. 1. In 1977, a new flying wing concept was patented and provided additional innovations to the current EWP concept.² This design had inlets and nozzles at the wing leading and trailing edges and buried engines in the wing, providing a completely distributed thrust for the vehicle from the wing tip to tip.

OBJECTIVES

Today's modern materials, aircraft control techniques, and computational aerodynamic and structural design may enable the promise of embedded wing propulsion to be more fully realized. The concept of Embedded Wing Propulsion or EWP is to install many propulsive engines within a wing structure so that it maximizes vehicle benefits by coupling propulsion and wing aerodynamics. In this concept, all propulsion related components such as inlets, engines and nozzles are located within the wing structure so that the coupled aerodynamic advantage between wing and propulsion system can be maximized. This may now be possible with the rapid advancement of engine designs with high performance and reliability, in addition to advances in CFD technology that will enable engineers to optimize such a concept for a very efficient vehicle.

From the beginning of this concept formulation, the followings have been identified as possible benefits:

- Reduction in aircraft drag and weight by eliminating engine nacelles.
- Reduction in aircraft drag through wing wake fill-in with engine thrust stream.
- Reduction in fuel consumption by ingesting thick boundary layer flow.
- High lift via high aspect ratio vectored thrust wing trailing edge nozzles providing powered lift, boundary layer control and/or supercirculation around the wing enabling short take-off capability.
- Jet flap capability using spanwide vectored thrust stream during short take-off and landing.
- Reduction in aircraft noise.
- Improvement in safety through a redundant propulsion system.
- Reduction in aircraft weight through inlet/nozzle/wing structure integration.
- Elimination of aircraft control surfaces through differential and vectoring thrust for pitch, roll, and yaw moments.

- Easy engine replacement provided that engines are small and lighter.
- Application of non-traditional engine concepts such as the multi-fan engine or constant volume engine that may be more applicable to the EWP concept. The constant volume engine will be ideal for supersonic aircraft where the wing needs to be thin compared to subsonic aircraft.

However, because of its inherent characteristics of integrating the propulsion system within the wing structure, the followings are identified as possible disadvantages:

- Increased internal flow drag.
- On board engine maintenance difficulty due to the embedded engine installation.
- Engine blade burst into airframe.

Additionally, there are several items that were considered in the past to be disadvantages due to their complexity but that may now have solutions because of modern design and analysis techniques:

- Fuel storage and distribution to many engines.
- Aerodynamic/propulsive design optimization.
- Aerodynamic/propulsive coupling causing control complexity.
- Structural design complexity.
- Multidimensional noise propagation.
- Integrated engine cycles for low specific fuel consumption.
- Inlet/nozzle design for extreme shape change.

The objectives for the current study are to analyze some of the above areas using a NASA's 800 passenger BWB design as a baseline and to provide guidance to future generation aircraft design using distributed propulsion. In this paper, some of early analysis and the current status of the study are presented.

EMBEDDED WING PROPULSION CONCEPT

To demonstrate the feasibility of the EWP concept, a 800 passenger Blended-Wing-Body (BWB) transport aircraft was chosen as the baseline model and studied by repositioning and distributing its propulsion system along the wingspan. From the beginning of this study, engine sizing was an issue and it was decided that a moderately small size engine such as the General Electric's CF34 with low specific fuel consumption was more ideal for the large BWB with EWP. Table 1 shows the number of required engines based on the 800 passenger BWB study by Liebeck.³ In addition, it was determined that modification of the original BWB payload volume structure was to be avoided so that there is minimal impact on overall vehicle structure. These two requirements then led to two versions of an EWP design as shown in Fig. 2 and 3. Fig. 2 shows configuration A with engines all buried inside the wing between the payload volume and the outer wing. This configuration has inlets and nozzles near the wing leading edge and trailing edge respectively, and provides direct powered lift using thrust-vectoring nozzles. Fig. 3 shows configuration B with engines all integrated within the BWB's wing trailing edge. For this configuration, higher propulsive efficiency may be achieved by ingesting all or a large amount of upper wing surface boundary layer flow. Ref. 4 describes the benefits of ingesting wakes or boundary layer flows on propulsive efficiency. However, because the inlets ingest thick boundary layer flow generated by the upper surface of the wing, the pressure recovery and flow distortion at the engine fan face plane may be compromised. In addition, powered lift for configuration B would be difficult to achieve due to the nozzle location being near the vehicle trailing edge and away from the vehicle center of gravity, causing large pitching moment.

In order to assess the benefits of thrust vectoring near the wing trailing edge, simple 2-dimensional computational fluid dynamics (CFD) simulations were performed using a NACA0012 airfoil, truncating the last 15% of airfoil chord and replacing it with a thrust vectoring jet flow or jet flap. Fig. 4 shows the geometry. For this initial study, an inlet is not included in the geometry for simplicity and due to an as yet

undefined inlet configuration. In addition, the intent of this study was primarily to demonstrate the effect of the airfoil trailing edge thrust vectoring jet on airfoil pressure distribution, lift and drag. For the simulation, a general purpose Navier-Stokes CFD code (WIND)⁵ was used and a turbulent (Spalart-Allmaras one-equation) model was implemented. Table 2 shows the computational boundary conditions in the free stream and at the jet nozzle exit plane. Figure 5 shows the effect of the jet at the end of modified airfoil on lift and drag coefficients. The lift and drag coefficients are based on free stream conditions and the original untruncated NACA0012 airfoil chord length. They are calculated by integrating only the upper and lower airfoil surface pressure distributions without including the vectored jet force contribution to the lift. In addition, the momentum or ram drag of the airflow in the jet is not incorporated into the force accounting. The study was performed at the low speed condition of $M_\infty=0.2$ with $M_j=0.95$ while varying angle-of-attack, α , and jet angle, θ . Positive θ implies that the jet flow is leaving downward from the airfoil trailing edge nozzle, providing both powered lift and thrust at the same time. At a fixed $\theta=30^\circ$ and various positive α 's, the lift coefficients are all positive and increase as α increases, proving that the trailing edge jets provide extra circulation around airfoil as if there is a flap near the trailing edge. Also, the drag coefficients are very low and, in fact, for α lower than 12° , they are negative suggesting that there is forward thrust, i.e., a large airfoil leading edge suction force, rather than a net drag on the airfoil. However, it is noted that, because the jet is at a vectored angle, there is a loss in net axial jet force that corresponds to $F_j(1-\cos(\theta))$ which must be accounted for during overall vehicle force calculations. Also, a similar study was performed at fixed $\alpha=0^\circ$ and various θ 's to see the effect on lift and drag of increasing jet flap angle. As the jet angle is deflected more downward, i.e. larger jet angle, the lift coefficients are increased and drag coefficients are decreased, suggesting that the supercirculation caused by jet flap is providing higher lift and forward thrust. Again, the forward thrust is generated by the large suction force near the wing leading edge. Finally, Fig. 6 and 7 show Mach number contours and surface pressure distributions of the jet flap airfoil at the various angles-of-attack and jet angles, showing how the flow changes around the airfoil in the presence of the jet flap.

OTHER DISTRIBUTED PROPULSION CONCEPTS UNDER NASA'S RAC PROJECT

In addition to the subsonic transport application of the EWP concept, two other propulsion/airframe integration concepts are being considered for these initial system level studies: a supersonic transport and a cross flow fan.

Supersonic distributed propulsion concept

For supersonic transport vehicle design, the Georgia Institute of Technology (Georgia Tech) is leading a system analysis effort on the business jet and 300 passenger sized vehicle concepts. A traditional supersonic aircraft typically incorporates podded propulsion designed for the supersonic environment but conceptually similar to a subsonic aircraft. The isolated propulsion system pods cause vehicle penalties that this vehicle study at Georgia Tech will help to quantify.

For supersonic flight, an added drag term results from the shock waves surrounding the vehicle. Depending on the vehicle configuration, this 'wave drag' may constitute from 10 to 50% of the overall vehicle drag. In addition to the wave drag, the shock waves will coalesce to varying degrees to cause a sonic boom at the ground. A significant contribution to the boom signature is caused by the propulsion pods. By carefully integrating the propulsion pods into the wing structure, a novel configuration that will reduce wave drag and thus have greater overall mission efficiency might be possible. Such a notional vehicle concept is shown in Fig. 8. For this vehicle concept, two conceptual propulsion systems are being considered. For a short-term development cycle, traditional gas turbine engines will be evaluated. On a longer time horizon, a novel propulsion system, utilizing distributed power and perhaps electric fuel cell power, is beginning to be investigated. To produce the required lift, additional swept wing panels outboard of the engine nacelle panels may be required.

In terms of supersonic wing design, the delta planform is a compromise between subsonic and supersonic aerodynamics. The low lift curve slope causes low wing loading and compromised supersonic

cruise performance. Georgia Institute of Technology's Advanced System Design Laboratory has developed and continually updates a system level approach to vehicle/mission design. The tools that are being developed will be coupled to propulsion system sizing / low and high speed aerodynamics / sonic boom prediction and elements of structural design to create a fully integrated aircraft design. An optimal vehicle design will be synthesized and evaluated. Final comparisons will be made to the evolved High Speed Civil Transport (HSCT) developed during NASA High Speed Research (HSR) program.

Cross flow fan concept

For low speed application, the concept of a cross flow fan or transverse fan has been proposed and investigated for many years. The fan is a 2-dimensional spanwise propulsor that are integrated within a wing structure to distribute the thrust along the wingspan. Fig. 9 shows one such configuration where the fan ingests the air from the wing upper and lower surfaces and ejects the air toward the wing trailing edge.⁶ In this configuration, two gas generators mounted at the wing-root and the wing-tip transmit the power to the transverse fan rotors that are placed near the wing trailing edge and connected by flex-couplings or universal joints. However, due to low performance of the fan and difficulty of installation within an aircraft wing structure, the concept was never put into practice. Under the NASA's RAC project, there are currently two separate efforts by the United States Naval Post-Graduate School and Syracuse University to improve the performance of the fan by using advanced experimental and CFD techniques and to analyze the concept at a vehicle systems level. It is hoped that, at the end of these two studies, a high performance cross flow fan may be realized and applied to future air vehicles with short take-off and landing, and efficient cruise capabilities.

CONCLUSION

The current status and some early analyses of the Embedded Wing Propulsion (EWP) concept being investigated under NASA's Revolutionary Aeropropulsion Concepts or RAC project are presented. The idea behind the concept is to fully integrate or embed a propulsive system within a wing structure to maximize vehicle benefits by coupling propulsion and wing aerodynamics. In a way, the concept is to emulate nature by taking a cue from birds. Similar to birds, the EWP concept provides adaptable thrust without any propulsive devices exposed outside the airframe and with very high performance and safety for all flight.

To study the feasibility of such concept, an 800 passenger Blended-Wing-Body (BWB) vehicle was chosen as a baseline configuration and was modified with the EWP concept. Even for this very large aircraft, a number of moderately small size engines with low specific fuel consumption rate was chosen because of physical constraints. For the initial study, two vehicle configurations were proposed. The design for one configuration is to completely bury the engines inside the wing between the wing leading edge inlets and trailing edge nozzles. The other design has the engines installed near the wing trailing edge so that the engines ingest large amount of boundary layer flow for high propulsive efficiency.

In order to assess the benefits of thrust vectoring near the wing trailing edge, a simple 2-dimensional computational fluid dynamics (CFD) study was performed using a modified airfoil with jet flap. The study showed large lift coefficients and unusually negative drag coefficients at various flow conditions. These enhanced aerodynamics are caused by the trailing nozzle jet performing like virtual flap by providing strong suction force at the airfoil leading edge.

Based on the initial conceptual study and the possible benefits that are proposed, the concept appears to be adaptable to a wide range of missions with very efficient performance from take-off to landing. The EWP concept does require high efficiency, suitably sized engines and systems that can be incorporated within a wing structure. In addition, if the propulsive engines are completely integrated with wing airframe, as if the airframe is a part of the engine or the engine is a part of the airframe, greater benefits might be realized. The EWP concept provides a nontraditional configuration to incorporate modern design tools and technologies with intent to significantly reduce air transport costs, enable new missions and enhance safety.

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Engines	General Electric GE-90	General Electric CF34	Williams International FJ22
Length (inches)	193	129	41
Weight (lb)	16700	2400	80
Thrust (lb)	90000	12700	700
Diameter of fan (inches)	123	45.6	14.5
Number of Engines Req'd	~2	~14	~264

Table 1. Conventional engine selection comparison for 800 passenger BWB with Embedded Wing Propulsion concept.

	Free stream	Tail-jet at nozzle exit plane
Mach No.	0.2	0.95
Total pressure (psia)	14.7	22.15
Total temperature (°R)	520	520

Table 2. Flow conditions for NACA 0012 airfoil jet flap CFD study.



Fig. 1. Some early aircrafts with various propulsion system placements.

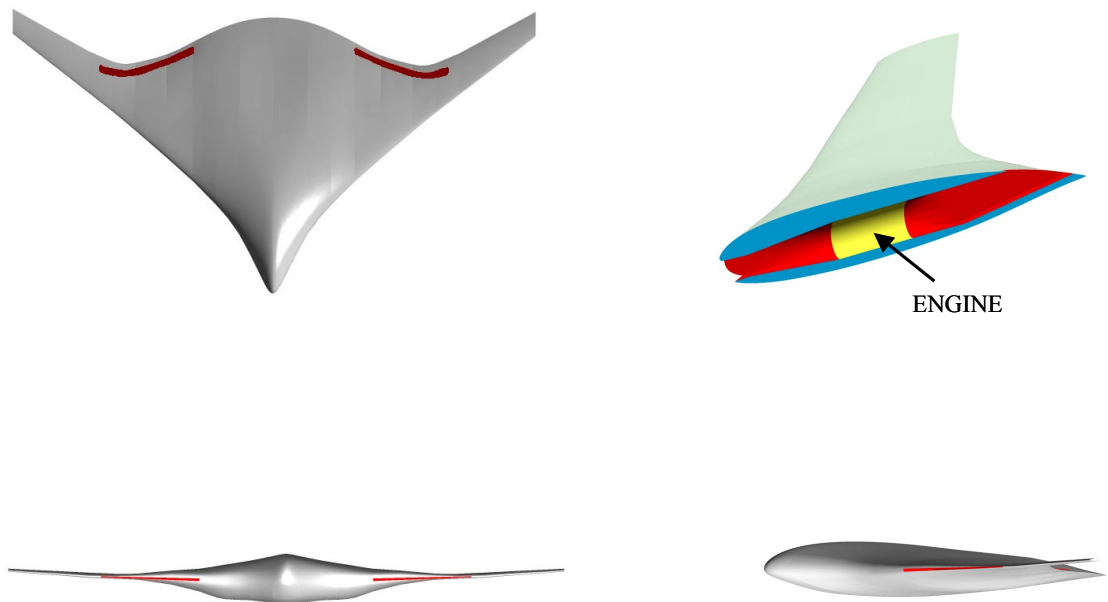
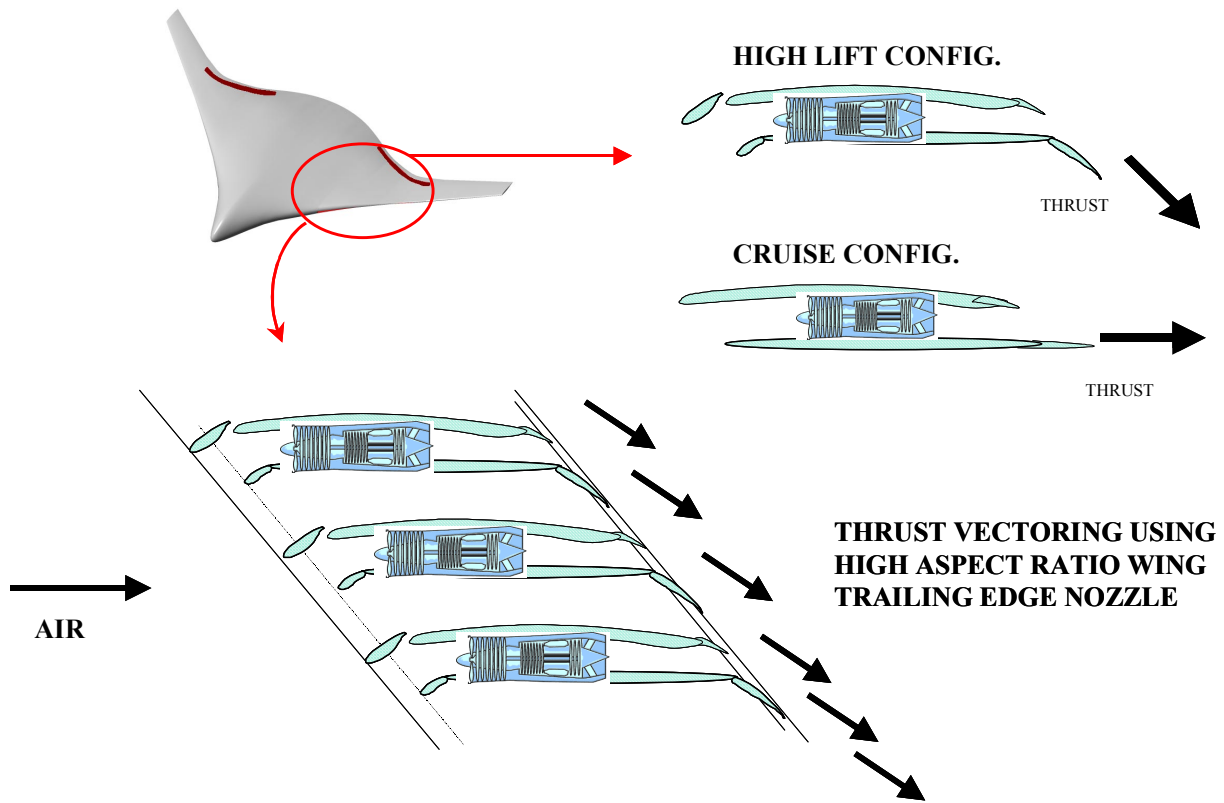


Fig. 2. Configuration A. A notional Embedded Wing Propulsion (EWP) configuration with engines all buried in the wing using a baseline 800 passenger BWB configuration.

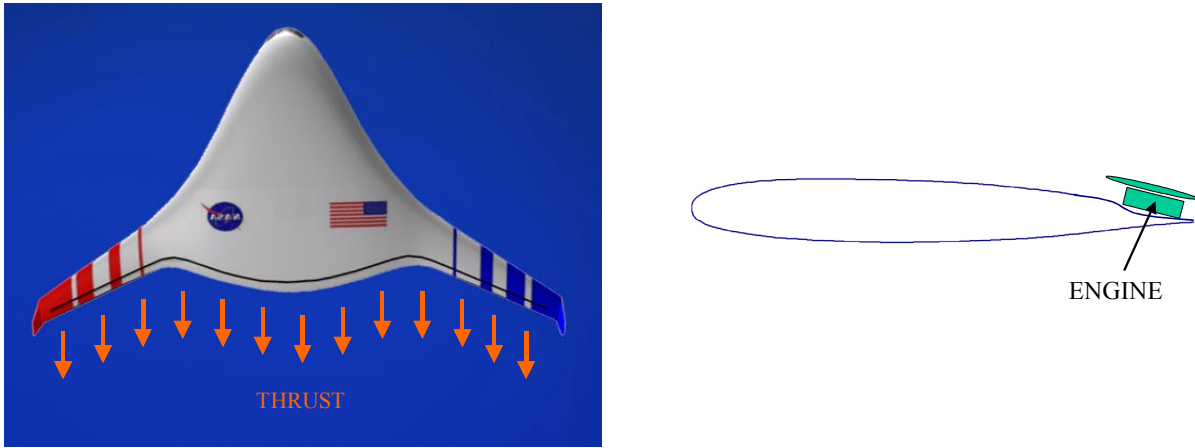


Fig. 3. Configuration B. A notional Embedded Wing Propulsion (EWP) configuration with engines all integrated with wing trailing edge using a baseline 800 passenger BWB configuration.

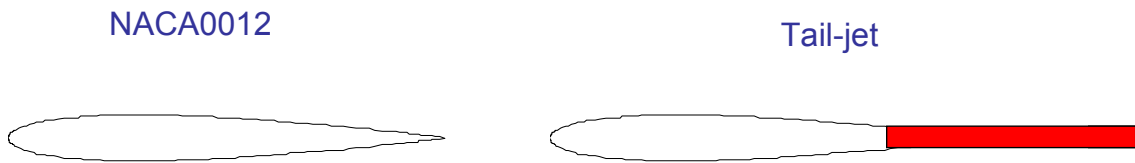


Fig. 4. NACA 0012 airfoil with thrust vectoring tail-jet or jet flap by truncating the last 15% chord and replacing it with jet flow.

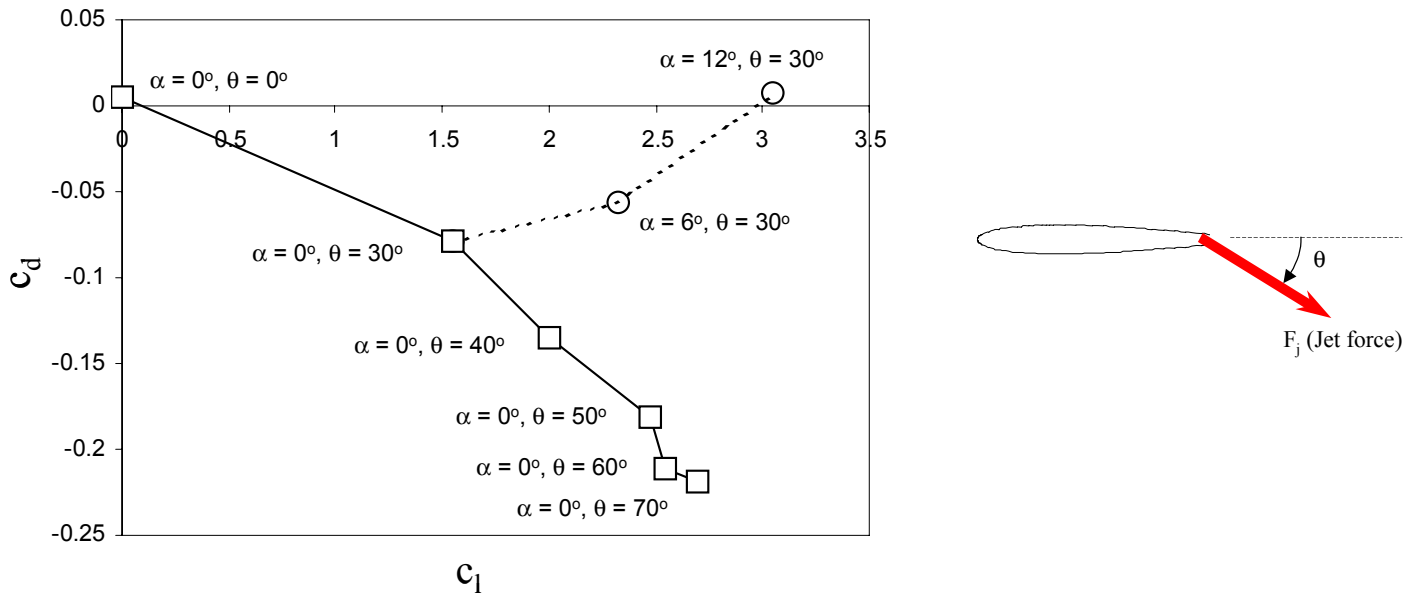
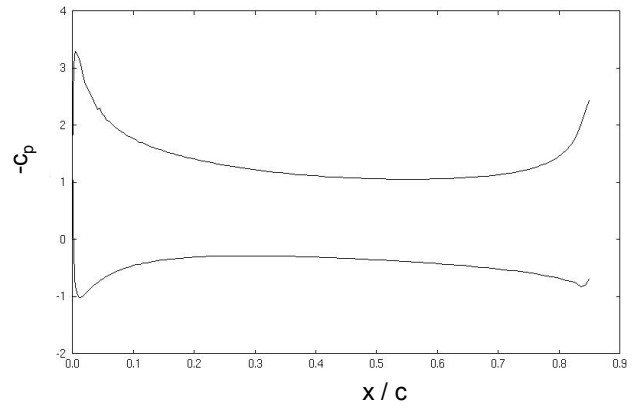
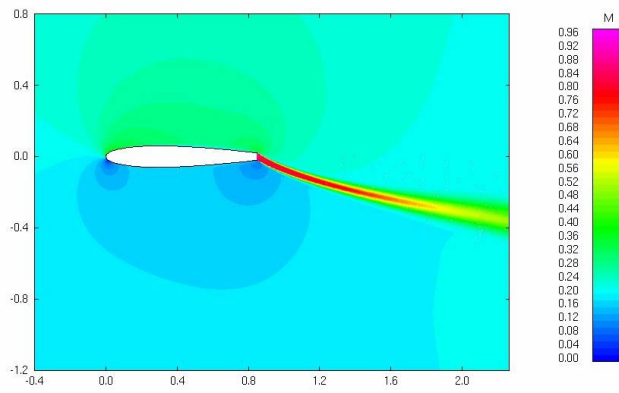
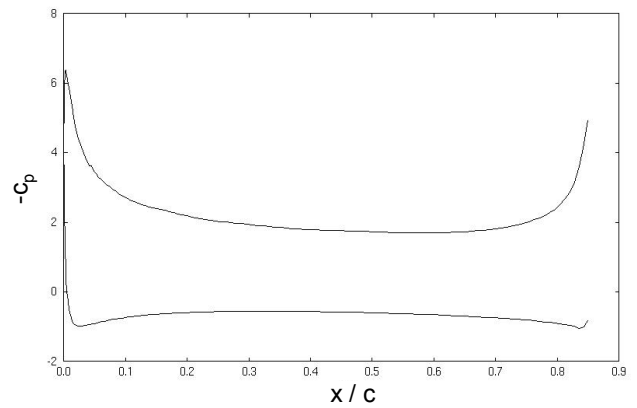
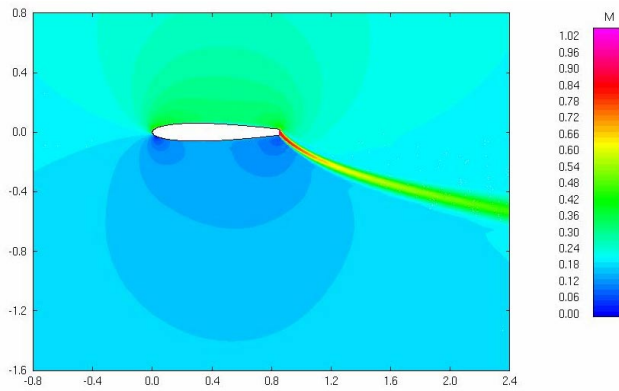


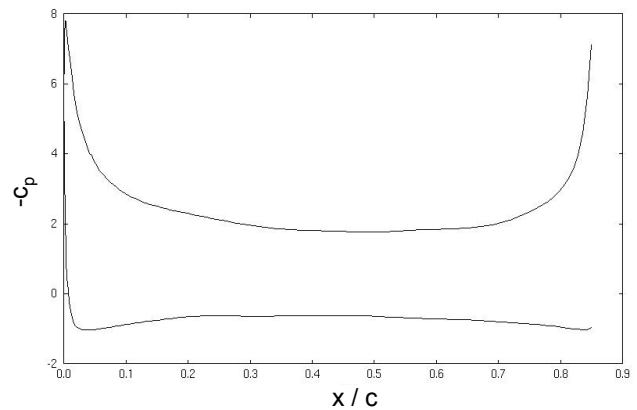
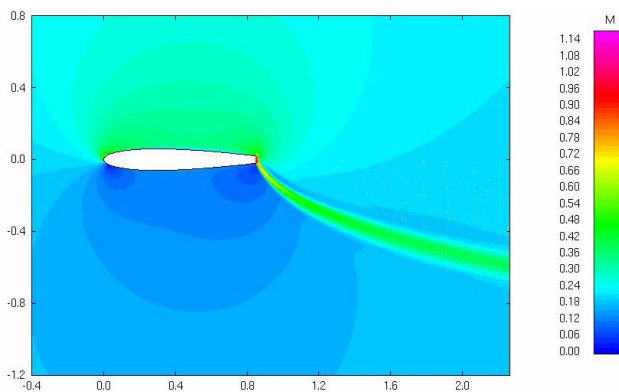
Fig. 5. Effect on lift and drag coefficients by varying angle-of-attack (α) and jet angle (θ) at $M_\infty = 0.2$, $Re/(ft) = 1.388 \times 10^6$, $M_j = 0.95$.



(a) Jet angle, $\theta = 30^\circ$.

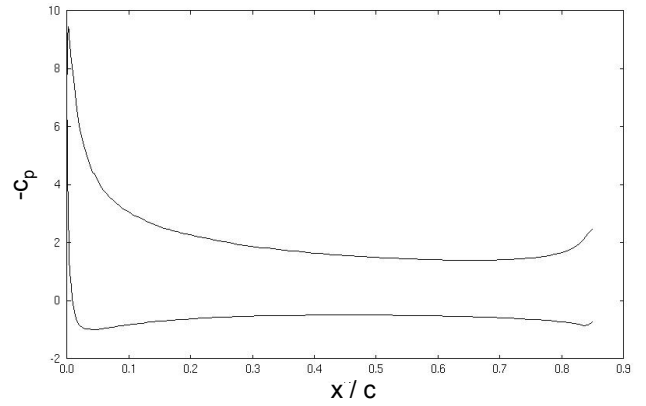
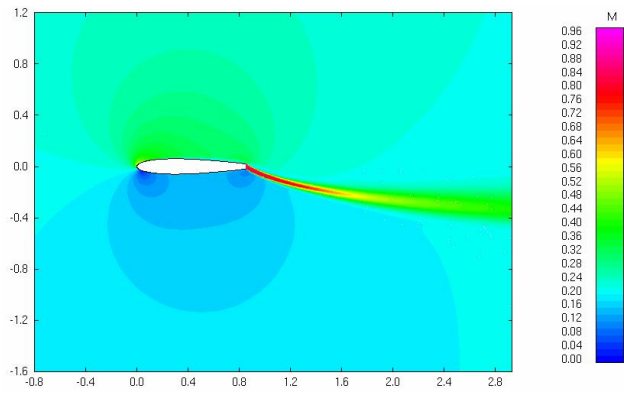


(b) Jet angle, $\theta = 50^\circ$.

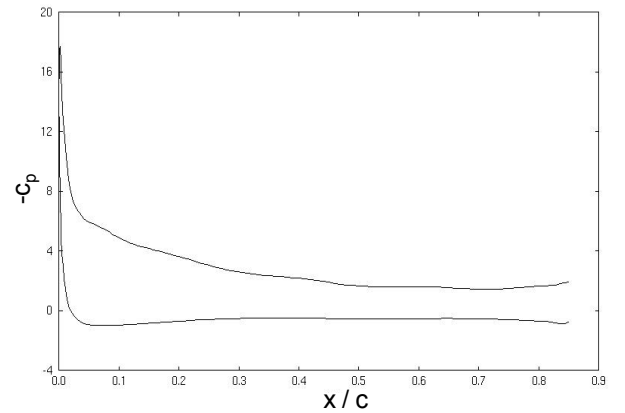
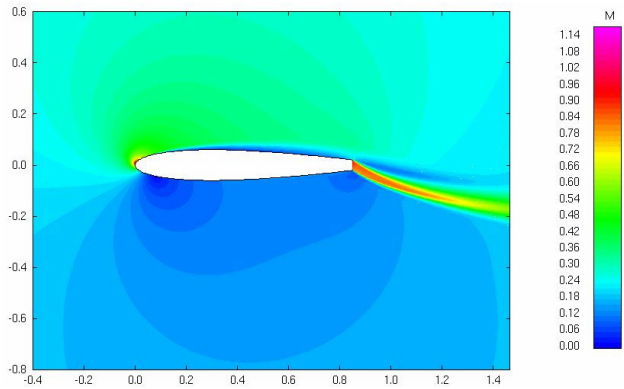


(c) Jet angle, $\theta = 70^\circ$.

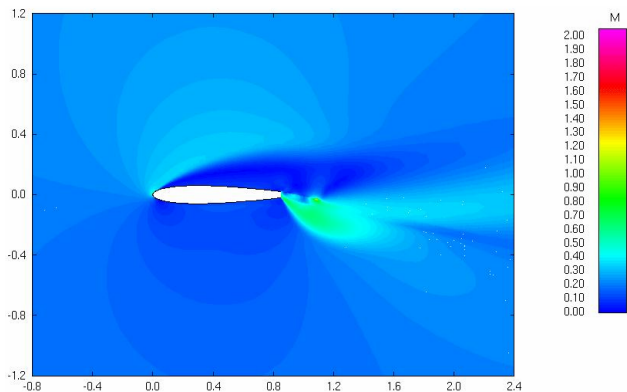
Fig. 6. Mach number contours and surface pressure coefficient distribution at various jet angle, θ , and constant angle-of-attack, $\alpha = 0^\circ$ ($M_\infty = 0.2$, $Re(ft) = 1.388 \times 10^6$, $M_j = 0.95$).



(a) Angle-of-attack, $\alpha = 6^\circ$.

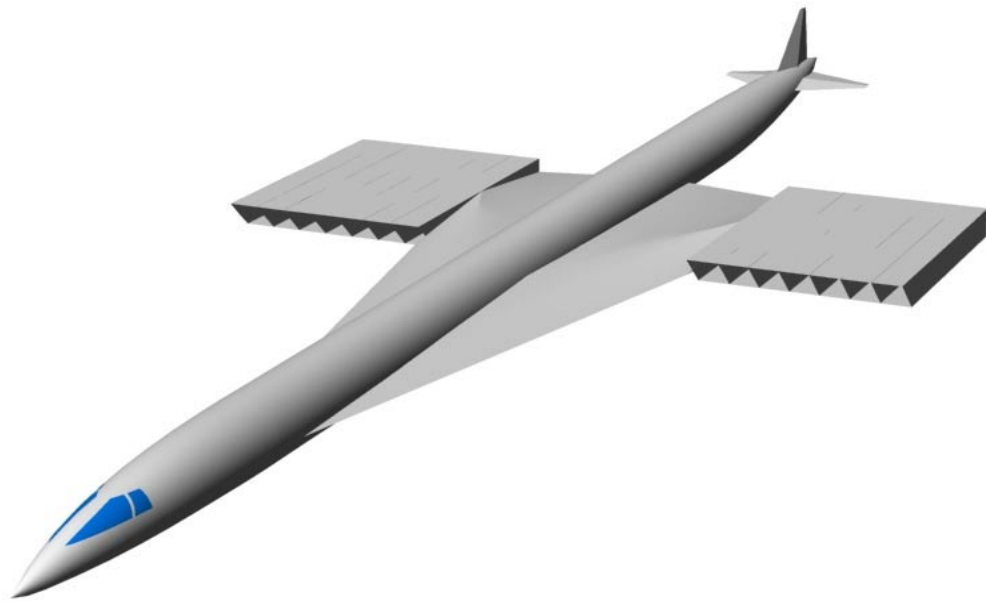


(b) Angle-of-attack, $\alpha = 12^\circ$.



(c) Angle-of-attack, $\alpha = 16^\circ$. Converged CFD solution was not obtained due to large flow separation.

Fig. 7. Mach number contours and surface pressure coefficient distribution at various angle-of-attack, α , and constant jet angle, $\theta = 30^\circ$ ($M_\infty = 0.2$, $Re(/ft) = 1.388 \times 10^6$, $M_j = 0.95$).



Notional Drawing

Fig. 8. A baseline concept for Supersonic Transport (SST) with embedded propulsion system.

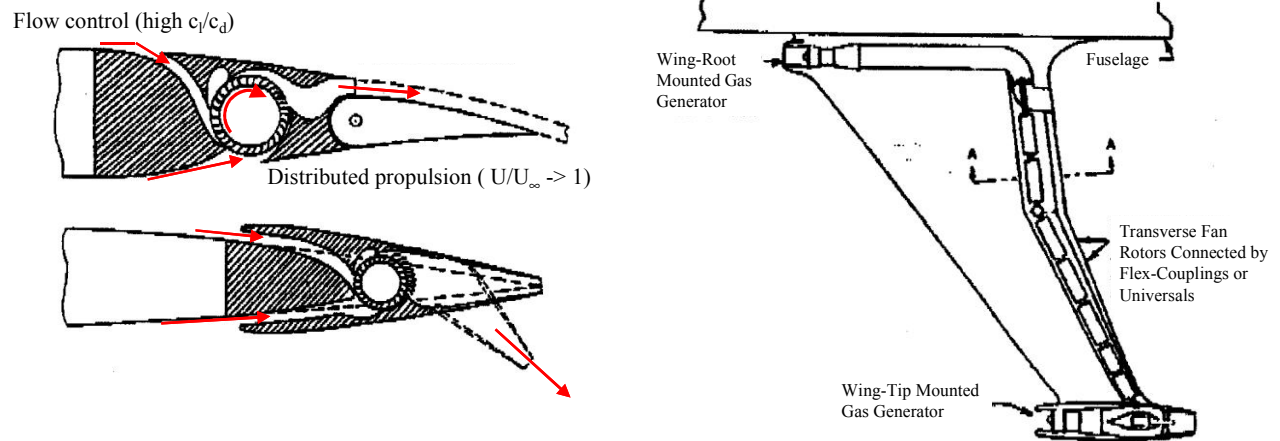


Fig. 9. A cross flow fan or transverse fan concept applied to aircraft wing.⁶

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE November 2003	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE Embedded Wing Propulsion Conceptual Study			5. FUNDING NUMBERS WBS-22-708-87-19	
6. AUTHOR(S) Hyun D. Kim and John D. Saunders				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-14199	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-2003-212696	
11. SUPPLEMENTARY NOTES Prepared for the Vehicle Propulsion Integration Symposium sponsored by the NATO Research and Technology Agency, Warsaw, Poland, October 6-9, 2003. Responsible person, Hyun D. Kim, organization code 2400, 216-433-8344.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Categories: 01 and 07 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) As a part of distributed propulsion work under NASA's Revolutionary Aeropropulsion Concepts or RAC project, a new propulsion-airframe integrated vehicle concept called Embedded Wing Propulsion (EWP) is developed and examined through system and computational fluid dynamics (CFD) studies. The idea behind the concept is to fully integrate a propulsion system within a wing structure so that the aircraft takes full benefits of coupling of wing aerodynamics and the propulsion thrust stream. The objective of this study is to assess the feasibility of the EWP concept applied to large transport aircraft such as the Blended-Wing-Body aircraft. In this paper, some of early analysis and current status of the study are presented. In addition, other current activities of distributed propulsion under the RAC project are briefly discussed.				
14. SUBJECT TERMS Engine airframe integration; Propulsion system configurations			15. NUMBER OF PAGES 18	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	