Final Report

Flight validation of cruise efficient, low noise, Extreme short takeoff and landing (CESTOL) and circulation control (CC) for drag reduction enabling technologies

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Purpose

The primary objective of this Seedling Fund research is to develop and prepare for flight, an innovative, affordable test bed aircraft that will allow integrated flight-propulsion control law and aircraft systems development, system integration, measurement of integration effects on performance, and early flight evaluation of circulation control technologies such as Cruise Efficient Short Takeoff and Landing (CESTOL) and Fundamental Aerodynamics Subsonic Transonic Modular Active Control (FAST-MAC) either separately or in combination. Once developed, the test bed aircraft will allow researchers to evaluate circulation control technologies in a flight environment and develop the technology for future commercial applications.

The secondary objective of this effort is to evaluate in-flight dual radius circulation control trailing edge flaps. This is the first time this technology that enables STOL performance with cruise efficiency will have ever been evaluated in flight. The testing will allow a comparison with a baseline version of the PTERA aircraft to measure take-off and landing performance as well as cruise performance.

The final objective of this effort is to develop tools for circulation control flight research. A six degree of freedom nonlinear flight simulation of the vehicle will be developed for the research community. The simulation will include the baseline aircraft as well as the circulation control data. Simulation data will come from previous wind tunnel tests and flight tests of the aircraft. These tools will help researchers develop flight controls and algorithms which can then be flown on the test bed aircraft.

Background

Background: Vision- CESTOL Airliners to reduce Airport Congestion

"The FAA estimates that increasing congestion in the air transportation system of the United States, if unaddressed, would cost the American economy $22 billion annually in lost economic activity by 2022" according to an FAA fact sheet.

The FAA Next Generation (NextGen) Air Transportation System Project is transforming the current Air Traffic Control System to address this issue. NextGen, in addition to modernizing current guidance, arrival and departure technologies and procedures, is opening the door for new aircraft types like CESTOL that will significantly contribute to reducing air traffic congestion, flight delays and airport noise. The unique capabilities of Castrol aircraft accomplish this in three ways:

1. By using underutilized shorter runways at larger airports
2. By using smaller underused airports in metropolitan areas
3. By using STOL flight trajectories to keep offending aircraft
   Noise within airport boundaries

Figure 1 Artists Concept of a NextGen CESTOL airliner

Background: Current Circulation/Active Flow Control Research

The number of flight operations at many of the nation's largest airports is projected to increase in the future. In order to meet increased mobility needs, the Next Generation Air Transportation System (NextGen) will rely on the expanded use of secondary and reliever airports which will employ a new class of vehicles that are capable of short take-off and landing (STOL).

Use of active flow control for drag reduction is also being investigated. For example, AFC could be used to reduce the size of aircraft vertical tails and their associated drag by using synthetic jets to reduce flow separation. This research is currently being done by Boeing under a NASA Funded study as shown I figure 2. The NASA Fundamental Aerodynamics Subsonic Transonic Modular Active Control (FAST MAC) is also investigating use of circulation control for drag reduction and is developing wind tunnel models for future testing as shown in figure 3.

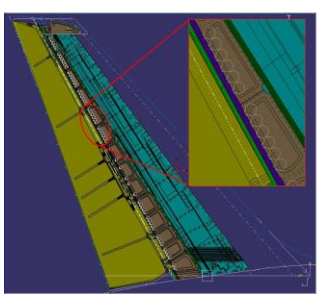

Figure 1 Synthetic Jets for Flow Reduction

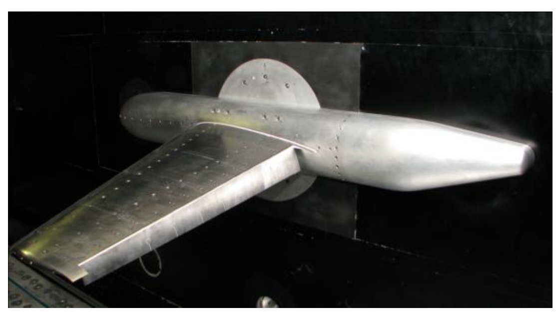

Figure 3 FAST MAC Wind Tunnel Model

Individual technologies to enable these future vehicles are being developed on computers, being built in laboratories and being tested in wind tunnels. Recent wind tunnel tests of the Advanced Model for Extreme Lift and Improved Aeroacoustics (AMELIA) showed improvements to lift performance with circulation control. AMELIA is a 1/11 Scale Wind tunnel model of a future 100 passenger CESTOL aircraft. The model was built and tested in a wind tunnel under collaboration between NASA Ames Research Center and Calpoly San Luis Obispo. Over 290 data runs were made in the National Full-Scale Aerodynamics Complex (NFAC). The AMELIA wind tunnel model is shown in Figures 4 and 5.

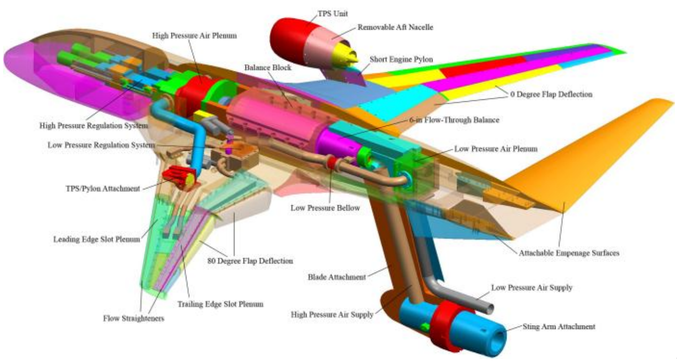

Figure 4 Cutaway drawing of AMELIA model Figure 5 AMELIA model in NFAC

Integration of these technologies with other aircraft systems and performance evaluation in a flight environment is critical in developing these future STOL and AFC vehicles but is not currently a focus of the NASA Fixed Wing program. This is in part due to the high cost of developing and operating a research test bed aircraft.

Under this project, a highly flexible and affordable circulation control research test bed and associated tools will be developed to increase TRL of technologies developed in the lab and wind tunnel.

Background: Benefits of Flight Research and Evaluation of New Technology

Flight research and evaluation has proven crucial for moving new technology and ideas from the laboratory, simulator and wind tunnel to use in the real world. One of many examples is the digital flight control computer which is standard now in all commercial and military aircraft. This technology was developed in the 1970's by NASA using a surplus Project Apollo guidance computer and an F-8 test aircraft. This progression is shown in Figure 6/

Figure 6 Development of the Digital Flight Control Computer thru flight research

Flight research enables maturity of new research and technology in the following ways:

- Focuses on the overall aircraft not components (wings, engines, flight controls, etc.)
- Provides integration and performance evaluation of new technologies with conventional/existing aircraft systems
- Provides insight into operational challenges such as flight control law design, aircraft handling qualities, transients and unsteady flow effects, stall and upset characteristics

Despite proven benefits, few new technologies go beyond laboratory or wind tunnel tests to full or seven sub-scale flight evaluation and to use in the real world due to several reasons including:

- High costs in developing and testing a new dedicated X-plane
- High costs and difficulties modifying existing aircraft and aerodynamic and circulation control test beds
- Time to build or modify a test aircraft requires early program funding and non-changing research priorities.

Under this research effort the goal is to be able to fly circulation control technology much earlier in the program cycle at a cost similar to wind tunnel testing in order to find implementation problems early and to provide a path to move research from the lab to commercial transports in order to realize all the benefits of the technology.

Approach

The overall technical approach will be to modify the baseline Area-I Prototype Technology Evaluation and Research Aircraft (PTERA) research vehicle as a Circulation control technology flight test bed. PTERA is a 10%-scaled Boeing 737 like research vehicle with an 11 foot wingspan, developed under the NASA SBIR/STTR program by Area-I. The baseline PTERA Aircraft was flown for the first time in July 2012 under a NASA Phase 1 SBIR contract. Under a current follow-on contract, the vehicle is being extensively tested and evaluated as a research platform by Area-I, and will be delivered to NASA at the end of the contract for future flight research. An overview of the approach is shown in Figure 7.

The PTERA aircraft itself is highly innovative in two major ways. First, it is highly reconfigurable allowing evaluations of various aircraft technologies such as truss braced wings, box wings, trailing edge dual-radius flaps, and different aircraft configurations (t-tail, straight wing, swept wing). Second, its large size and large payload area reduces scale effects, as well as allowing installation of various combinations of circulation control technologies.

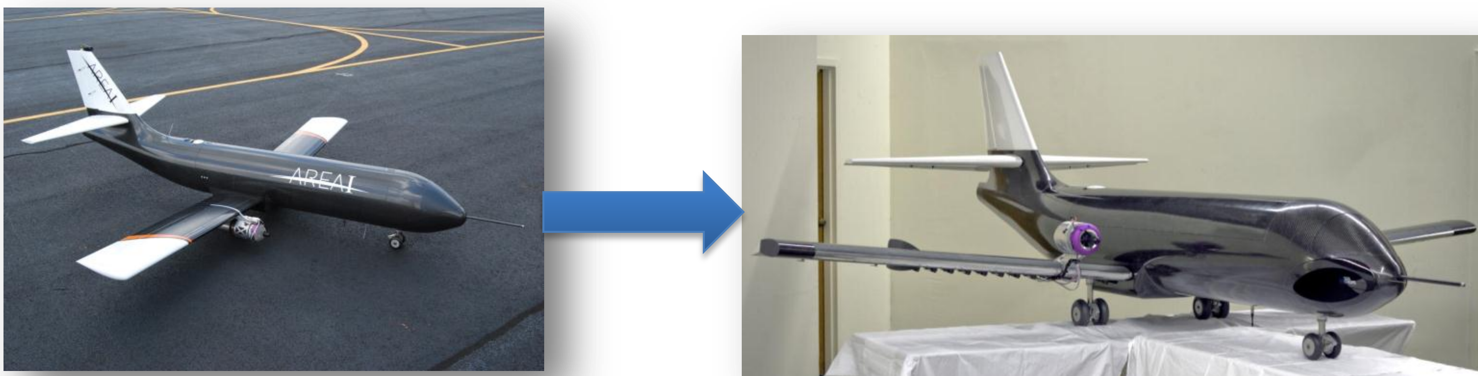

Figure 7 Highlights of conversion from PTERA BL to PTERA C3

In Phase 1, three CESTOL/FAST-MAC technologies: leading edge blowing for flow separation control, trailing edge dual-radius circulation-control flaps for short take-off/landing performance and cruise efficiency, and over-the-wing, thrust vectored powered lift for lift augmentation will be integrated on the aircraft and thoroughly tested (Figure 8). Hardware for these three technologies has already been fabricated and integrated on the PTERA.

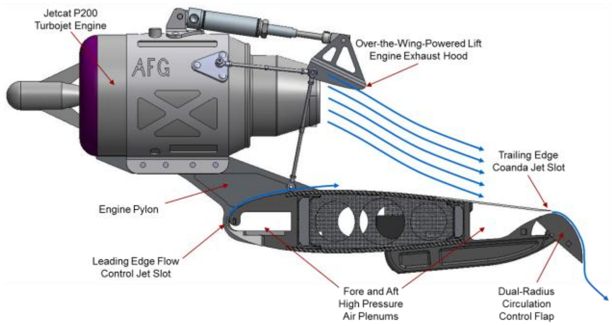

Figure 8 PTERA Circulation Control Technologies

Accomplishments

Initial meetings with researchers at NASA Ames and some primary discussions with researchers at NASA Langley provided valuable insights in defining test objectives and data requirements as well as providing them with information on this research effort. A briefing on the seedling fund work and the resulting follow-on discussions at the International Powered Lift Conference yielded additional inputs. These inputs allowed evaluation of the aircraft instrumentation and its ability to support test objectives.

Most of the effort over the first six months was developing the PTERA simulation. In addition to aerodynamic models described below, an engine model, a simple flight control system and PTERA mass properties were added to the simulation

Development of aerodynamics models from PTERA wind tunnel and flight test data was the other major task accomplished during this time period. Aerodynamics data tables were generated by Area-I using their *WingsX* software.

Aircraft modifications to convert the PTERA aircraft to the PTERA C-3 configuration have been completed. The PTERA Baseline wings, engines and other equipment have been removed. PTERA-C3 ducts were repaired and the compressors, engines, dual radius trailing edge flaps and other associated equipment have been installed.

During the last week of January 2014, the PTERA C-3 was successfully ground tested at Georgia Tech Research Institute (GTRI). All systems were functionally tested, and the circulation control flow characteristics of the dual radius trailing edge flaps were measured.

Successful ground testing will enable flight evaluation of the PTERA C-3 aircraft and dual-radius flaps during Phase 2 if awarded.

Status of Research

Simulation Development

Aerodynamics models of the PTERA Base Line aircraft were created using Area-I's *WingsX* software. Data for the models were taken from wind tunnel and flight test data collected during previous research efforts. These models will form the basis of the 6 DOF nonlinear simulation being developed as part of this research effort. Both the aerodynamics models and the simulation will be available to the circulation control research community.

Limited circulation control aerodynamic models from wind tunnel testing have also been developed by Area-I but are not yet added to the simulation. These models will be added to the PTERA baseline simulation once it is working correctly. A flag in the simulation will allow either the baseline or circulation control aerodynamics models to be used.

Jet Cat P200 engine data from engine test runs was added to the simulation. Current plans will be to use a Jet Cat P200 engine for flight testing PTERA circulation control. Modifications to the engine models for thrust vectoring will be added during the second half of the task.

A simple, flight control system architecture was added to the simulation. Currently only conventional flight control surfaces (elevator, ailerons, rudder) are commanded. Once circulation control models are added these control laws will be expanded.

Currently the simulation is running with the PTERA baseline models but is not trimming correctly compared to the Area-I simulation. Once these issues are resolved, other circulation control related models can be added to the simulation. It has been difficult to obtain the required support from the flight simulation branch due to higher priority projects.

Aircraft Modification

The modification of the PTERA airframe to accommodate the C3 systems has been completed. The avionics, fuel system, and actuator control system were removed to facilitate the installation of the compressors, ducting, flow control systems, and the compressor inlet ducts near the nose of the aircraft all of which have now been installed. Figure 9 shows an overall view of the PTERA C-3 compressors, ducting and the leading and trailing edge plenums. For the dual-radius trailing edge flap flight evaluation, only the aft plenums will be used. Future experiments could use forward, aft or both plenums depending on the technology being evaluated.

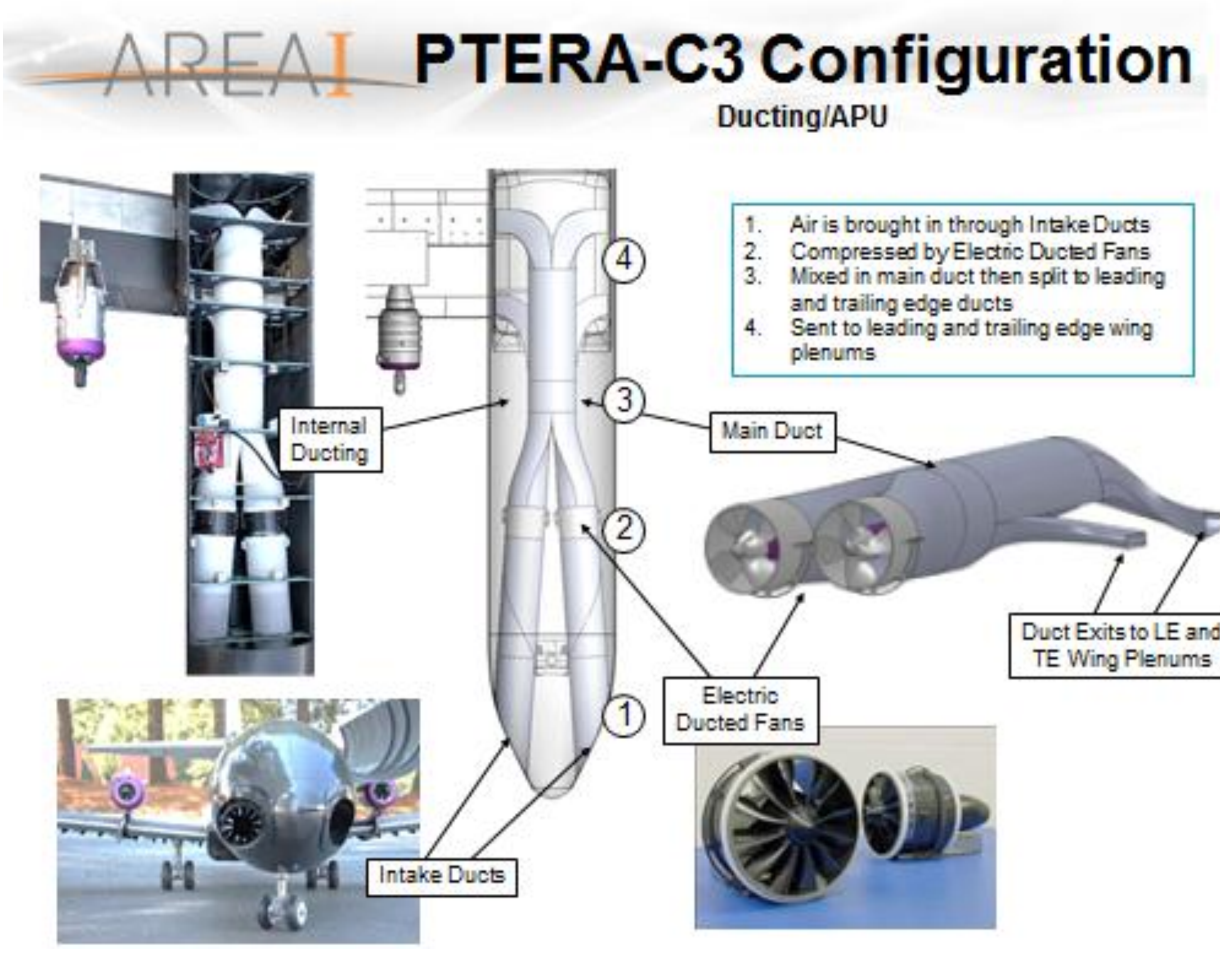

Figure 9 PTERA-C3 Configuration Ducting and APU Schematic

In addition to the compressor and ducting, electronic components were all installed in the aircraft. This included compressor controller and batteries, flow gate and compressor controller interface, plenum flow gates and actuators, PTERA avionics computer, and plenum pressure instrumentation. The layout of aircraft electronics is shown in Figure 10.

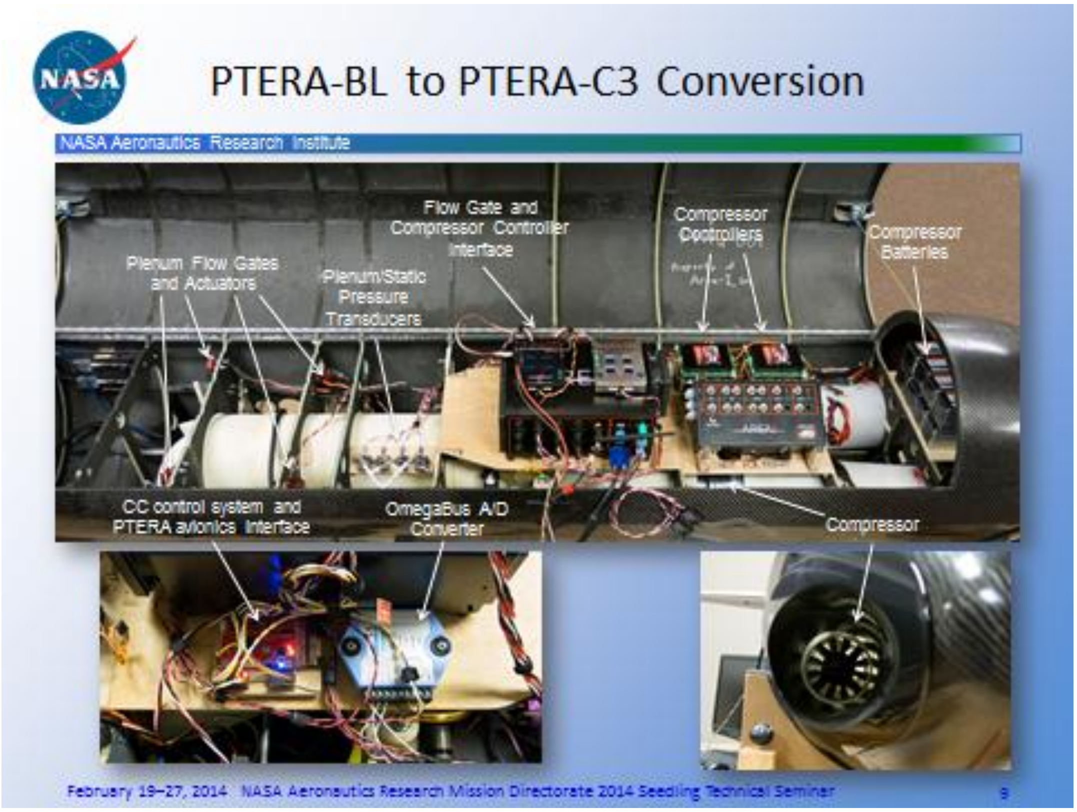

Figure 10 PTERA C-3 Electronics Schematic

The final major modification was to replace the PTERA baseline wing with the PTERA C-3 wing. The PTERA C-3 wing is especially designed for circulation control research. Compressed air from the leading and trailing edge plenums is distributed across the wing thru slots providing energized an energized air source for circulation control experiments. Slot heights are adjustable across the wing span allowing a uniform mass flow from wing root to tip.

For the first flight evaluations, dual-radius, colanda flaps have been installed on the C-3 wing. The wing has been designed so that the leading and trailing edge are no-structural allowing different flaps to be installed and evaluated in flight. The PTERA C-3 with dual-radius flaps is shown in Figure 11.

Figure 11 PTERA C-3 Wing with Dual- Radius Trailing Edge Flaps

Ground Testing

Completion of modifications to convert PTERA-BL to the PTERA-C3 configuration, were completed in early January 2014 allowing for a ground test of the aircraft during the last week of January 2014. Testing was performed at Georgia Tech Research Institute (GTRI). GTRI provided data acquisition facilities as well as technical support for the PTERA C-3 ground testing at no cost to the project. Because of the excellent support and expertise provided by GTRI, they have been included in the Phase 2 proposal as a collaborator.

The purpose of PTERA C-3 ground testing was to 1) functionally check all hardware and software, 2) check data measurement and recording software and hardware, 3) measure circulation control system performance. Test data was recorded and will be put in the PTERA C-3 simulation.

Functional tests of the circulation control and data measurement and recording systems were all successful, allowing the ground test to proceed to measure system performance. To obtain test data, a miniature pitot tube was used to measure jet slot velocities at several points along the trailing edge of both wings as shown in Figure 12. Jet slot velocities are used to calculate the momentum coefficient Cmwhich directly relates to dual-radius trailing edge flap STOL performance.

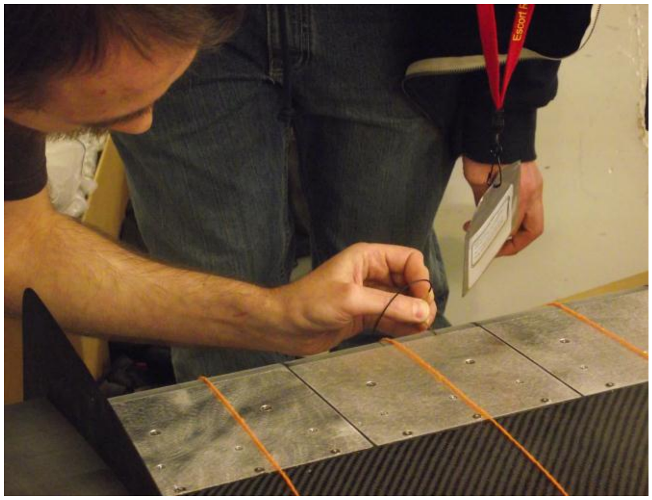

Figure 12 Measurement of PTERA C-3 jet velocities using miniature pitot tube

Jet velocity data was collected at several compressor throttle settings and plenum pressures. The test set-up is shown in Figure 13. Plenum pressure is controlled small aluminum plate in the ducting that acts as a guillotine-style flow gate as shown in Figure 14. An actuation system controlled by the test computer moves this gate up and down to vary plenum pressure.

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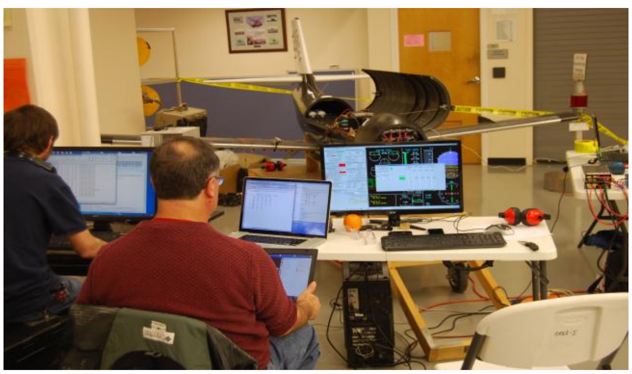

Figure 13 PTERA C-3 Test Set-up

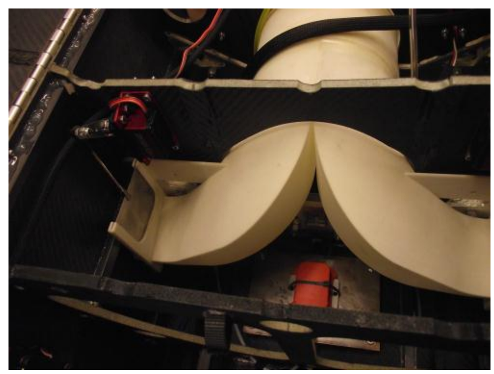

Figure 14 Aft Plenum Flow Gates

In addition to jet slot velocity measurements, photos were also taken to show trailing edge flap circulation control effects. Figure 15 shows the trailing edge without circulation control and Figure 16 shows it with circulation control and the colanda effect**.**

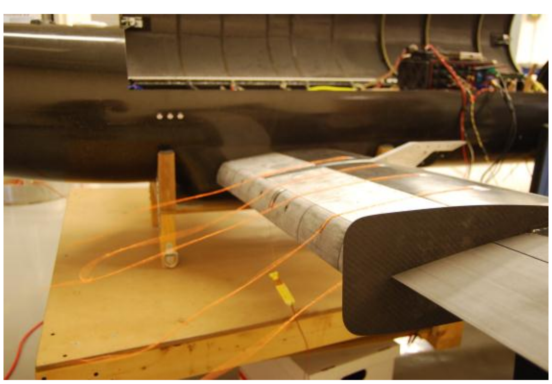

Figure 15 Trailing Edge without Circulation Control

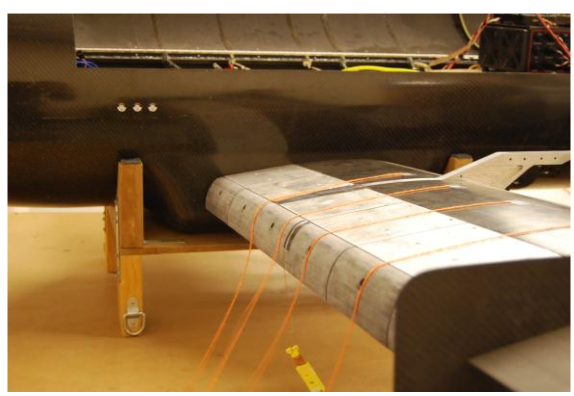

Figure 16 Trailing Edge with Circulation Control

Ground Testing Results

Ground testing of the PTERA C-3 aircraft took place the week of January 27 at GTRI. In summary all aircraft hardware and software functioned correctly leading the way for flight test of this technology in Phase 2.

Figure 17 shows maximum jet slot velocities measured along the left wing span at various compressor throttle setting and with completely opened flow gates. At two mid-span (15.75" and 21.75") locations additional measurements at various throttle and plenum gate settings were also taken. Averaged values at 18.75" are shown in the chart.

Ideally jet slot velocity should be uniform across the wing span. As shown on the chart, slot velocities are much lower near the wing root (spanwise position 0"). This was due to some blockage of the jet slots in that area due to other structure. This problem will be fixed prior to flight testing.

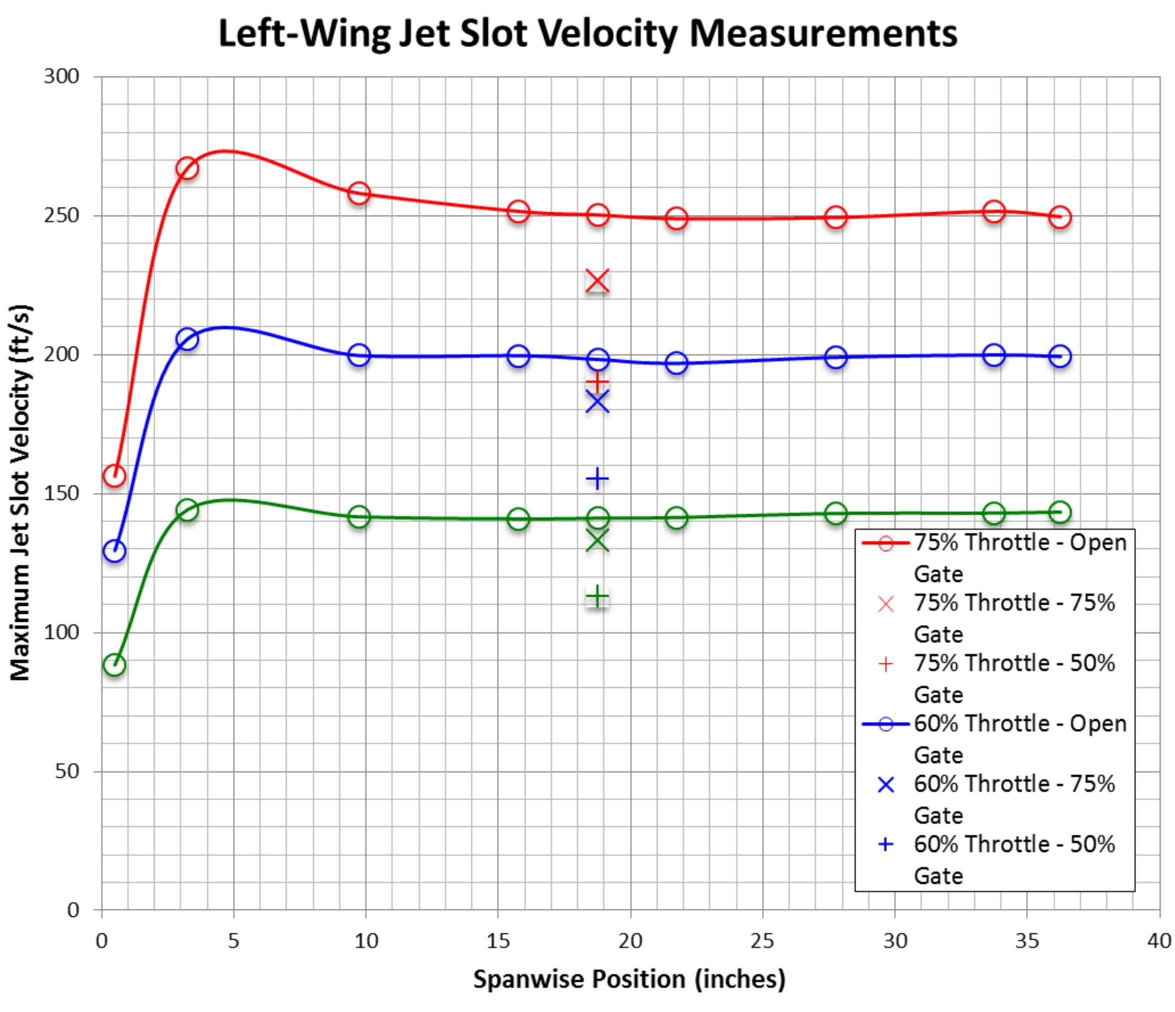

Figure 17 Plot of Jet slot velocities vs. span position for PTERA C-3 left wings

The momentum coefficient ὅ̦ varies with dynamic pressure by the equation:

ὅ̦   ά ὡ̦ /qS   where   ά is mass flow rate

ὡ̦ Is jet velocity

q Is dynamic pressure

S is surface area

Using data from PTERA C-3 ground testing, the momentum coefficient per unit span was calculated at 4 different airspeeds as shown in Figure 18 Note that the momentum coefficients presented here are based on the maximum slot velocities and assume a fully turbulent flow profile. . As velocity was 0 ft.sc during ground testing, these are predicted values that will be compared with flight test values obtained in Phase 3

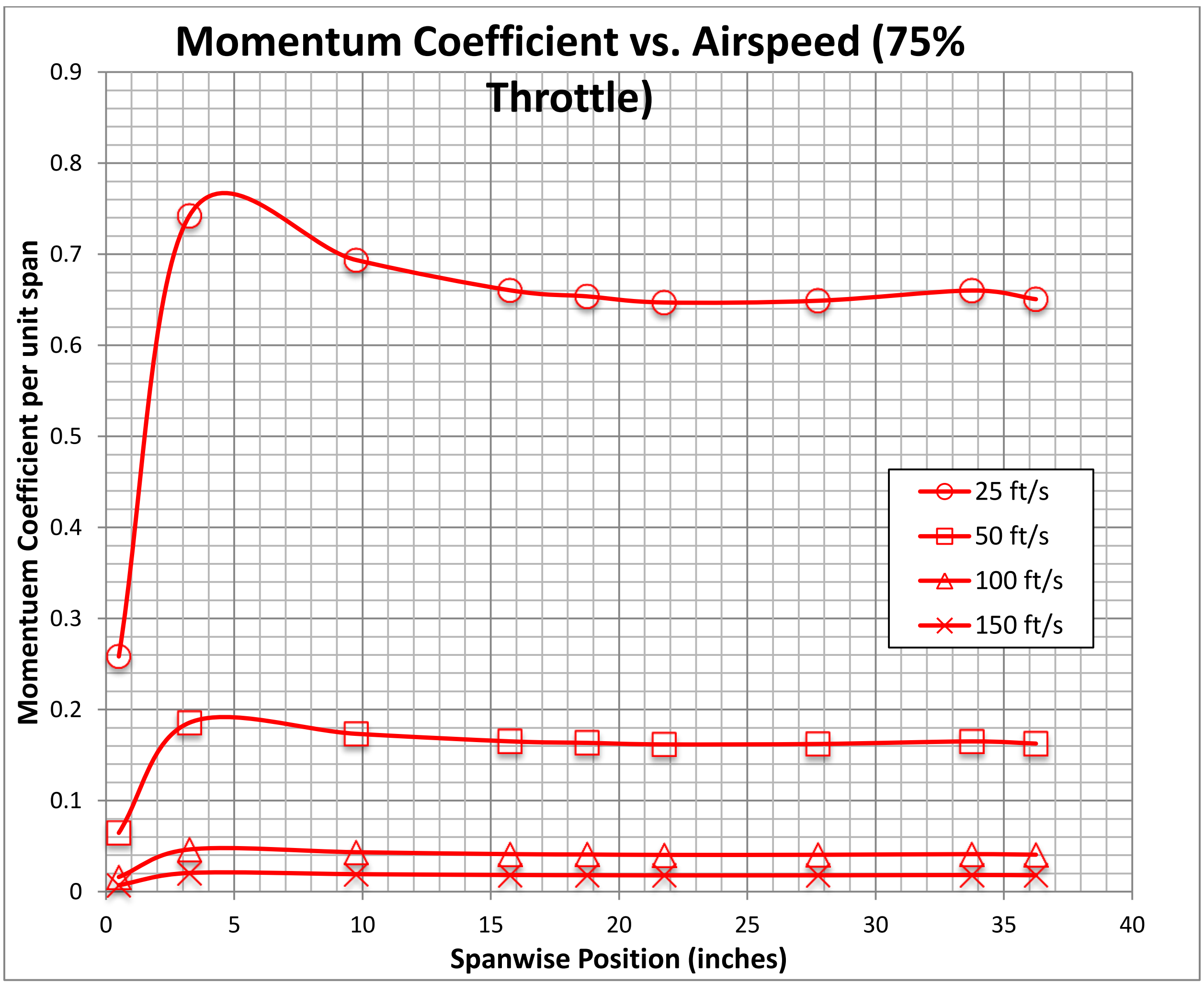

Figure 18 Momentum Coefficient vs., Airspeed for PTERA C-3 at 75% throttle

The PTERA C-3 Circulation control system was designed to provide a total ő̧ of 0.061 at an airspeed of 44 ft. /sec. Even at a reduced throttle setting this value is easily achievable. Predicted values were obtained from PTERA C-3 wind tunnel testing at GTRI under a previous NASA SBIR contract. Figure 19 shows lift coefficient increase of over 0.8 for a total ő̧ of 0.061 at an airspeed of 44 ft. /sec. Figure 20 is a photo of the PTERA C-3 wind tunnel model for this testing.

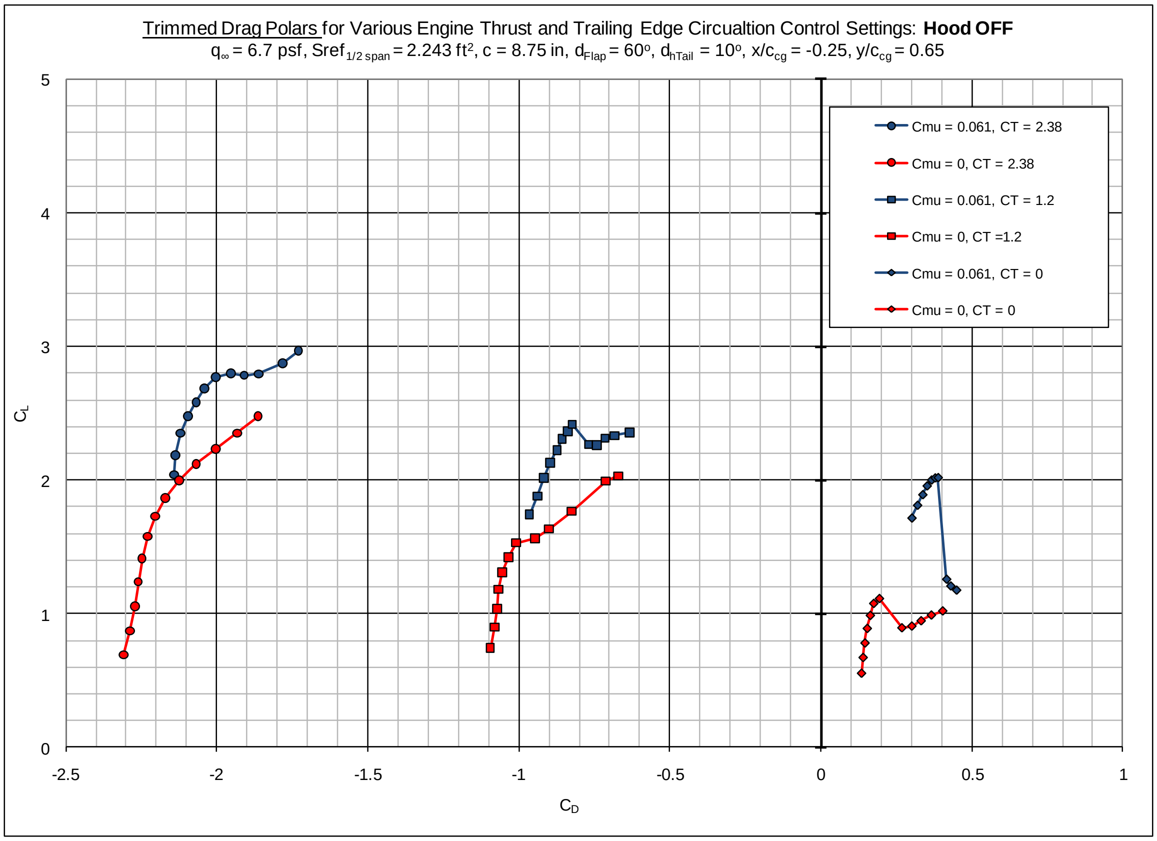

Figure 19 Trimmed drag polars for various engine thrust and trailing edge circulation control settings

Figure 20 PTERA C-3 Wind tunnel model

Current TRL

Current TRL for the PTERA C-3 test bed is TRL 6 as the aircraft is ready for flight and evaluation of the dual radius trailing edge flap. However the overall objective of this research is to be able to fly lower TRL (3-4) research on this aircraft to raise TRL of the technology.

Applicable NASA Programs/Projects

This work is directly applicable to the NASA Fixed Wing and the NASA Aeronautical Sciences projects under the

A Aeronautics Research Mission Directorate. Two specific projects that would benefit from this research are the FAST-MAC project and the AMELIA project which have been tested in a wind tunnel. .

Currently working with the NASA AFRC ARMD Research Coordinator to develop infusion plans for this technology into a NASA Program and with Boeing as a partner to develop this research for commercial use.

Publications and Patent Applications

A technical overview of this research was presented at the International Powered Lift Conference on August 12, 2013 in Los Angeles CA.

Awards & Honors related to Seedling Research

Currently there are no awards or honors associated with this seedling fund task