1st International Conference on Innovation and Integration in Aerospace Sciences
4-5 August 2005, Queen's University Belfast, Northern Ireland, UK.

CEIAT 2005-0086

Development of an Integrated Circulation Control / Fluidic Thrust Vectoring Flight Test Demonstrator

Russell Sparks*, Stephen Michie* and Ken Gill*
The Manchester of University, Oxford Road, ManchesterM15 9PL

Dr W. J. Crowther†, Prof N.J.Wood‡
The University of Manchester

This paper describes a six month project being undertaken at The University of Manchester to rapidly demonstrate flapless flight control technologies at model aircraft scale (AUW<7kg). The project is funded through BAE Systems and will contribute towards the integrated UK FLAVIIR UAV program. The project aims to gain open loop flight test data to allow the accelerated development of a closed loop flight control system and quantify the systems impact of the flapless control at model scale. The issues associated with general integration of Circulation Control (CC) and Fluidic Thrust Vectoring (FTV) are discussed and then a case study is presented which discusses implementation of the technologies on flight demonstrators. The world's first CC flight control demonstrator has been developed and flown.

Nomenclature

A = area (m^2)
C_D = drag coefficient
C_L = lift coefficient
C_{mo} = aerodynamic moment coefficient
$C_{M_{TV}}$ = thrust vector moment coefficient
C_μ = blowing coefficient
S = wing Area (m^2)
V = airspeed (m/s)
V_J = secondary Jet Exit Velocity (m/s)
c = wing mean chord (m)
k_n = static margin
l_t = tail arm (m)
$\dot{m}$ = mass flow rate (Kg/s)
q = dynamic Pressure
δ_{TV} = thrust vector deflection angle (^{o})
ρ = density (Kg/m^3)

---

[*] Postgraduate research Student, Manchester University, Goldstein Research Lab, Barton, Manchester, M30 7RU
[†] Lecturer, Manchester University, Oxford Road, Manchester, M15 9PL
[‡] Professor of Aerospace Engineering, Manchester University, Oxford Road, Manchester, M15 9PL

I. Introduction

A Fully operational flight control system based entirely on flow control technologies would enable the development of an aircraft with no external moving parts. This brings potential benefits in terms of reduced observability and reduced maintenance. This paper considers the application of two high authority flow control technologies to a UAV, namely Circulation Control (CC) for roll control and Fluidic Thrust Vectoring (FTV) for pitch control. See References 4 to 8 for more information. Although CC and FTV flow control technologies have existed for many years they have never been successfully implemented as primary flight controls, neither individually or as a complete system. The process of moving technologies from bench top experiments to flight ready technology has traditionally taken many years. This project aims to demonstrate a new approach where intensive short projects are used to produce model scale flight demonstrators which highlight implementation issues before integration of the technologies at full scale. The intensive projects aim to prove the technologies capability as flight hardware and provide a source of expertise allowing resources to be focused when implementing the technologies at full scale. This avoids costly misdirected research or unforeseen issues which inherently arise. This paper initially describes some of the integration issues associated with implementation of CC and FTV technologies and then presents a case study of a six month project which has produced the worlds first FTV and CC flight control demonstrators.

Circulation control is a method of providing roll control through asymmetric lift augmentation and is an alternative to conventional ailerons, but with additional benefits. Due to there being almost no moving parts, the system complexity is reduced, resulting in potentially higher reliability, cheaper construction and lighter weight. The system works by blowing a jet of air through a thin slot above a circular trailing edge as shown in Figure 1. This jet of air attaches to the trailing edge surface due to the Coanda effect, and it is the interaction between this Coanda flow and the free-stream flow that causes the flow deflection and control forces similar to that of a conventional aileron. The secondary jet velocity must be greater than the free stream velocity; the greater the difference the greater the control effectiveness. It is possible to have a flexible slot lip, only opening up when the pressure inside the plenum reaches a set limit.

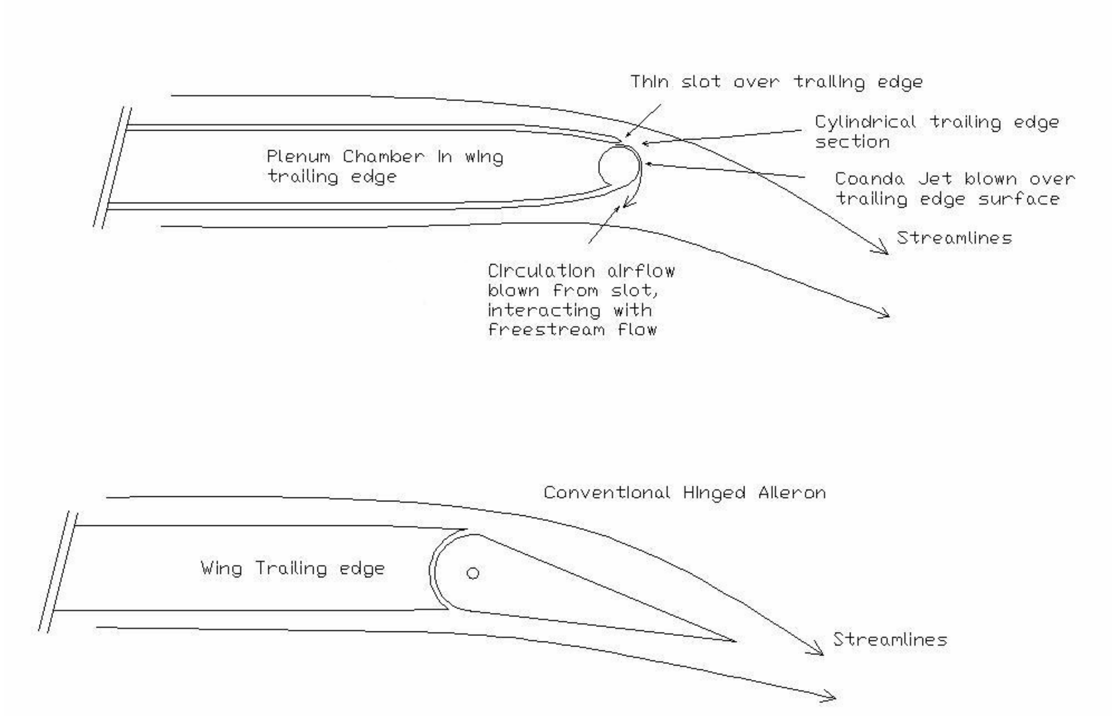

Figure 1. Diagram illustrating principles of Circulation Control

FTV is an alternative to mechanical thrust vectoring with a number of benefits. FTV allows a fixed geometry nozzle and duct reducing the mechanical complexity of the system which in turn may improve reliability and reduce weight. The system could be used to eliminate the need for elevator type controls as the forces produced should be adequate in magnitude, response time and controllability. FTV works in a similar way to CC however in FTV a secondary Coanda jet is used to control an adjacent primary jet rather than the free stream the secondary jet entrains the primary jet and due to the presence of a Coanda reaction surface the thrust is vectored. This results in a normal component of the thrust vector which can be used for pitch control.

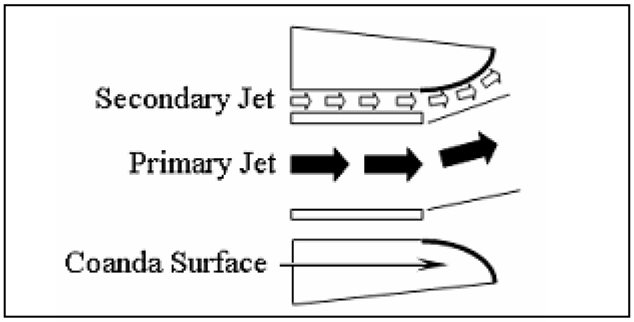

Figure 2. Diagram illustrating principles of FTV

From the brief descriptions of Circulation Control and Fluidic Thrust Vectoring, it is obvious that one of the primary integration issues for flapless flight controls is the provision of a secondary air supply to provide air at suitable pressure and mass flow for the control devices. If the main power plant is a large multi-stage gas turbine engine, then the compressed air can be supplied via bleed from the compressor. Alternatively, a second compressor can be driven via a shaft or electrical power off take from the main engine.

II. Discussion of Integration Issues

A. Aerodynamics

An aerodynamic penalty associated with CC is the increase in the wing drag coefficient due to the required circular trailing edge section. There are two potential solutions for this problem. The first is to optimise the geometry of the trailing edge. A hybrid triangular/circular trailing edge could be blended into the aerofoil section of the wing whilst still producing the control effectiveness of a circular trailing edge. Another potential solution would be to use two secondary jets, one above and one below the Coanda surface. By blowing simultaneously through both slots an artificial sharp trailing edge may be created. Response time may be reduced as the plenum chambers would already be at operating pressure. It is also possible that due to the fact that air is being blown constantly over the trailing edge, the baseline drag of the aircraft may actually be reduced. Provision of FTV nozzles at the back of an aircraft would also increase the Cdo of the configuration if not very carefully integrated.

B. Structures

. Using FTV the jet is vectored due to the presence of the reaction surface and hence this surface experiences a suction force which ultimately leads to a pitching moment. This moment acts through the nozzle and so the structure around this area must be adequately stiff and strong to bare these loads under high temperature conditions.

The fluidic flight control system requires the distribution of pressurised gas. This may lead to complex routing of ducts and so careful design is necessary to minimise losses through the system. An optimised structure could be designed around the pneumatic power system to ensure minimal pressure losses. An integrated solution could utilise pipe work as structural components with the aim of reducing the all up weight of the aircraft.

C. Pneumatic Power Distribution

As with all flow systems the energy losses are proportional to the fluid flow rate. These problems could be reduced with the use of a high pressure low flow rate system with conversion to low pressure, high flow rate at the CC or FTV plenums. The most feasible solution to achieve this appears to be the use of a jet pump. The jet pump entrains air into the primary jet resulting in a high mass flow low pressure. This possibility is under investigation.

D. Flight Control Systems

Conventional elevator type devices rely on free stream dynamic pressure to provide their control force, whereas FTV uses the thrust to create its control force. This dependency on thrust and therefore operating point leads to a nonlinearity in the control system. High thrust conditions allow high control force capability from the FTV system. This potentially allows large forces to be produced for example in take off.

For fixed slot CC the response time is governed by the valve opening time and is therefore comparable to conventional controls. Flexible slots are pre-tensioned and require a threshold pressure to be reached before the slots open. The entire system can be pressurised to a level that only requires a small increase before the threshold pressure is achieved. Combining this with a flight control system capable of monitoring pressures throughout the system would result in reduced response times.

E. Propulsion

An efficient vectoring system requires a high aspect ratio nozzle exit however the exit of a typical jet engine is circular. The FTV ducting must ensure the exit velocity profile is uniform and must minimise the pressure losses incurred over the cross sectional geometry change.

The option of engine bleed to provide the secondary air supply to the pneumatic control systems may result in a more complicated engine selection process. When bleeding from an engine the compressor and turbine operating points are moved from the optimum deign point and consequently an integrated design solution is required. This is an important consideration when integrating the flow control technologies with the propulsion system.

F. Configuration Design

The configuration design issues when applying fluidic controls are similar to those made for conventional controls. In the case of both CC and FTV the effectiveness of the controls are dependant on the moment arms and therefore dependant on the system's position relative to the centre of gravity. The requirement to pipe flow from the secondary air source to the hardware may also dictate the system configuration.

III. Case Study

A. Flight Demonstration

This case study describes a six month project being carried out by a team of PhD students at The University of Manchester. The project aims to rapidly demonstrate FTV and CC flight hardware at model aircraft scale (<7kg). Flight tests were conducted at Sale model club in Manchester while the 9' x 7' Avro tunnel and Environmental tunnel at Barton were available for wind tunnel tests. The project has been split into two stages. The first stage utilises off the shelf aircraft kits which provide ideal aircraft planforms for implementing the FTV and CC technologies. Therefore a dedicated CC demonstrator and dedicated FTV demonstrator have been designed. This allows the bench top experiments to be rapidly converted into flight hardware. The second stage of the project takes the flight hardware and optimises it for use on a realistic UCAV planform such as the X45A. This aircraft is referred to as the Integrated Demonstrator. The CC and FTV Demonstrators allow design and flight experience to be gained at an early stage of the project. This knowledge can then be fed into the design of the Integrated Demonstrator.

Figure 3 shows the design points of each of the demonstrators. A recommended wing loading region has been added to the graph. Exceeding this wing loading would lead to increased aircraft speeds and consequently difficult handling qualities particularly during landing. Each aircraft is designed with a relatively high power loading to allow responsive handling in case the aircraft should experience difficulty.

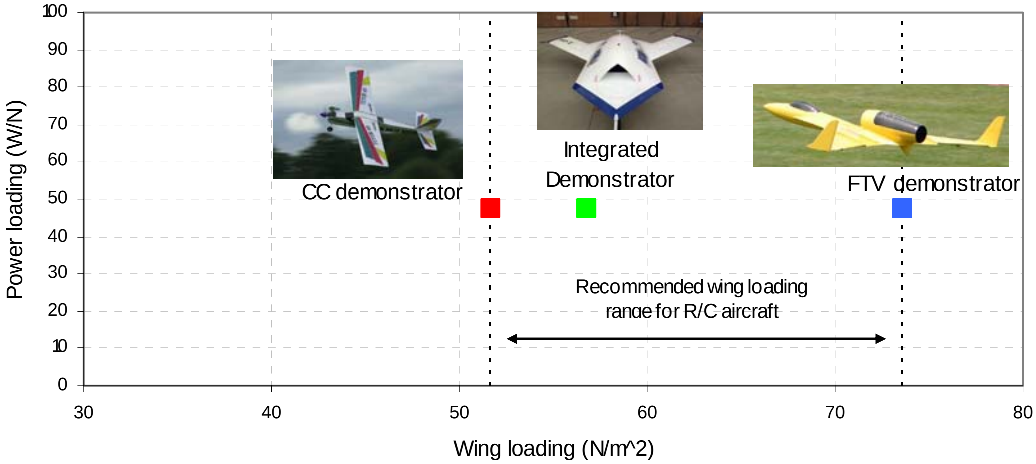

Figure 3. Sizing diagram for model scale aircraft

B. Development of a Secondary air supply

For the Manchester Seed Corn demonstrator aircraft as electric ducted fans (or a small internal combustion engine in the case of the CC demonstrator) were being used for primary thrust, the option of bleeding air from the compressor was not available. Thus two possible options were left; a compressed air bottled supply, or a separate on-board compressor. A bottled supply was almost immediately ruled out due to weight restrictions. Although suitably small high pressure bottles existed, it was found that even the smallest weighed almost 1 Kilogram empty. A decision was therefore made to use either an additional smaller electric ducted fan as a one-stage axial compressor, or a modified automotive turbocharger. The compressed air can be collected in a pressurised reservoir before being distributed to the control systems. A single-stage axial fan may tend to surge should the back pressure become too high for a given mass flow. This condition was experienced for the circulation control system due to the small slot area. However, for the Fluidic Thrust Vectoring system, the larger mass flow requirement meant that the secondary electric ducted fan was suitable.

Existing compressor maps for automotive turbochargers showed that the mass flow and pressure requirements of the flow control systems could easily be met. The compressor wheel is designed to operate at speeds of up to 120k RPM. Using a brushless motor it has been possible to achieve speeds of up to 30k RPM. Although below the designed operating point this provides the required mass flow and pressure. It was decided to manufacture a 2-piece compressor casing from carbon fibre to replace the original cast iron and aluminium housing. This would be lightweight and would also convert the centrifugal air compressor into an axial type that would be simpler to install in the chosen airframe.

Figure 4. Modified turbocharger unit with circulation control primary plenum chamber

Construction of this unit was carried out using a number of specially produced aluminium jigs for the internal and external surfaces. Testing was done simply by fitting a cut down soft drinks bottle over the exit of the compressor to provide an exit nozzle. From some initial bench testing of the unit in this configuration, a mass flow rate of 0.06Kg/s was measured as well as an operating pressure of almost 3kPa. This is suitable for both Circulation Control and Fluidic Thrust Vectoring on the demonstrator aircraft.

In order to integrate the turbocharger onto the circulation control demonstrator a separate primary plenum chamber was manufactured to fit directly to the rear of this unit, (See Figure 4). This pressure reservoir would be used to distribute the air at the required pressure to each of the flight control systems. The pressure reservoir was constructed from fibreglass lay-ups over specially made formers achieving a lightweight, integrated unit.

C. Circulation Control

The aircraft chosen to demonstrate Circulation Control roll effectors was the Irvine Tutor 40, shown in Figure 5. This aircraft is produced in an Almost Ready to Fly (ARTF) format from Irvine Ltd and is a high wing trainer type aircraft powered by a 0.46 cubic inch internal combustion engine. This type of aircraft was chosen as its low cruise speed, high stability and high power to weight ratio made it an ideal aircraft to install experimental equipment to, with minimal risk. The low cruise speed would allow a higher velocity ratio between the circulation control jets and the free stream resulting in more rapid roll response.

Figure 5. The Irvine Tutor 40

Initially, as the aircraft was designed purely as a rapid demonstration of Circulation Control, the decision was made to mount the secondary air supply and piping externally. Light weight butterfly valves were installed in the pipe work and the air flow was regulated by the speed of the compressor. A small processor chip was used to open the relevant control valve and spool the compressor up to a suitable speed dependant on the control input. The battery pack for the secondary air supply motor was mounted in the forward fuselage. To maintain roll control while the circulation control system was not operational, half-span ailerons were maintained on the inboard section of the wings. Plenum chambers were constructed with flexible slots. The tension of the slots could be adjusted to optimise the CC effectiveness based on wind tunnel data. The external equipment resulted in a large drag penalty as shown in Figure 6 and the CC system had to be integrated into the aircraft fuselage for flight tests.

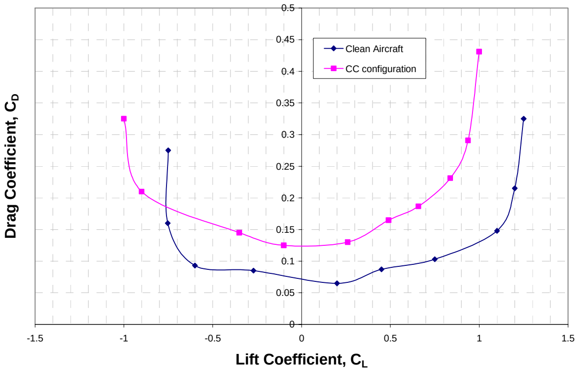

Figure 6. Lift vs. Drag for CC configuration against clean aircraft

In addition to the drag reduction exercise the aircraft weight was reduced. All pipe work was replaced with ultra lightweight flexible tubing provided generously by BWT Senior Aerospace. This tubing is used for the air conditioning ducts in the Airbus A380. In order to retain larger ailerons the plenum chambers were replaced by slightly smaller units constructed from balsa wood.

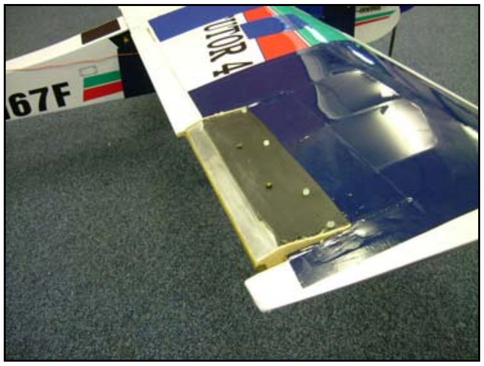

Figure 7. CC demonstrator plenum chamber in wing tip

The second configuration was tested in the wind tunnel and was found to have a similar C_{D0} to the clean aircraft. In addition, the weight saving measures had resulted in approximately 300grams being reduced from the overall aircraft weight as compared against the first circulation control configuration, though it was still 800grams heavier than the clean aircraft. While in the wind tunnel, the control effectiveness was also investigated. Theoretical predictions for equivalent span ailerons were calculated. When comparing these with wind tunnel results for Circulation Control (see Figure 8), it can be seen that they perform equally well. The graph illustrates the circulation control working at 50% or 100% of its capability, against an aileron with a 100% deflection angle of 20°. However, it must be noted that the circulation Control acts on one wing while ailerons act on two.

Following a flight using conventional controls, the circulation control was tried on a level fly-past. Roll control was clearly evident, though slightly delayed as the aircraft banked to the left to complete a full turn. Following this turn, software glitches in the circulation control processor prevented further demonstrations. Once the processor was de-bugged, and the flexible slots on the plenum chambers were adjusted to regulate the airflow more suitably, further flight tests were carried out. These were successful and the system was capable of demonstrating complete figure-8 circuits without any additional aileron control. Although at the time of writing, take-off and landings had not been demonstrated, it is felt that these are well within the capability of the system.

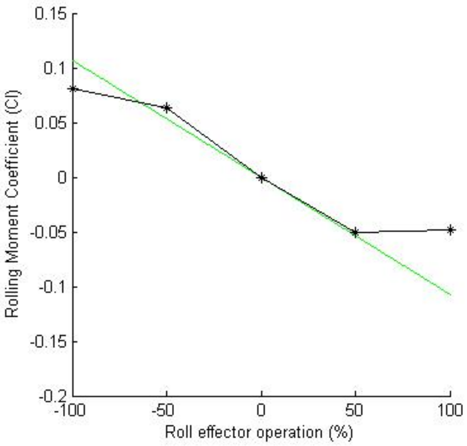

Figure8. Graph comparing wind tunnel Circulation Control data with predicted roll moment due to aileron deflection

Also, at the time of writing, a further wind tunnel programme was planned to further assess the effectiveness of the circulation control and to correlate this data with flight test data, monitored by on-board data-acquisition hardware. This flight test data will be real-time monitoring of airspeed, plenum chamber pressures and roll rate and will help to fully analyse the circulation control system in a free-flight situation.

C. Fluidic Thrust Vectoring

The FTV electric demonstrator will rapidly de-risk the new technologies on a model scale aircraft so that this experience can be fed into the FLAVIIR demonstrator system design. The baseline aircraft chosen is the off the shelf Schubeler Vector II. This aircraft was selected due to its prominently mounted engine allowing the modifications to be made without major structural changes. The standard Vector II aircraft has been flown weighing 2.75kg powered using 20xRC2400 batteries. The all up weight for our standard aircraft is 2.25kg. This weight reduction is possible due to advancements in power supply technologies; LIPO cells. This gives us a guideline of approximately 0.5kg for the additional technologies without exceeding a known weight capability for the Vector II planform.

Flight Duration (battery life) = 8.5mins
Thrust = 22N
Propulsion Weight Total = 918g per EDF unit
Overall propulsive system thrust to weight of around 2
Cruise Speed - 30m/s
Wing Span - 1.16m
Weight - 2.25Kg
EDF Propulsion

Figure 9. Vector II

The development of a flight ready FTV system for this scale aircraft in this time scale results in an un-optimised solution. In this case this is reflected in the secondary air supply choice. An additional smaller Schubeler fan will be used. Axial fans are usually operated in low pressure, high mass flow situations. The secondary flow source would ideally be a relatively high pressure and low mass flow. However due to weight and volume restrictions the option of using more advanced supplies, such as an electric turbocharger, is not an option on this aircraft.

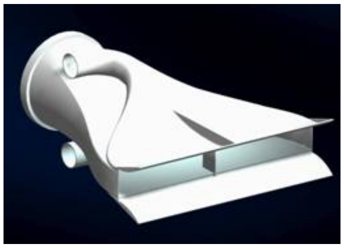

Figure 10. Vector II ABS Nozzle

The most crucial components for fluidic thrust vectoring are the high aspect ratio primary duct, the thin secondary slots and the reaction surfaces. These components have previously been made out of a number of separate parts. A more advanced technique of rapid prototyping (3D printing) using ABS plastic can be used to produce flight capable components for use with electric ducted fans. Figure 10 shows a Pro Engineer cad drawing which has been manufactured using this technique. With sufficient stiffening ribs the design can be made sufficiently stiff for flight whilst the one piece construction keeps weight down to a minimum.

Battery sharing is an integration possibility which will be exploited on the aircraft. By matching the brushless motor specification in the primary and secondary fans the voltage requirement can be such that both can be ran off the same power supply. This may reduce the flight time but enables the weight of the aircraft to be minimised.

Lightweight flexible tubing will be used for secondary air ducting with external sections appropriately faired. The mass flow will be controlled using simple butterfly valves. Blowing continually through both slots, allows a constant secondary fan power setting. This ensures rapid response times dictated only by the speed of the valve. Control is achieved by asymmetrically altering the flow through the slots.

Preliminary bench-top tests of the hardware show favourable results with vectoring clearly visible, see Figure 11. At the time of writing wind tunnel testing of the Vector II will commence within two weeks, followed by flight testing.

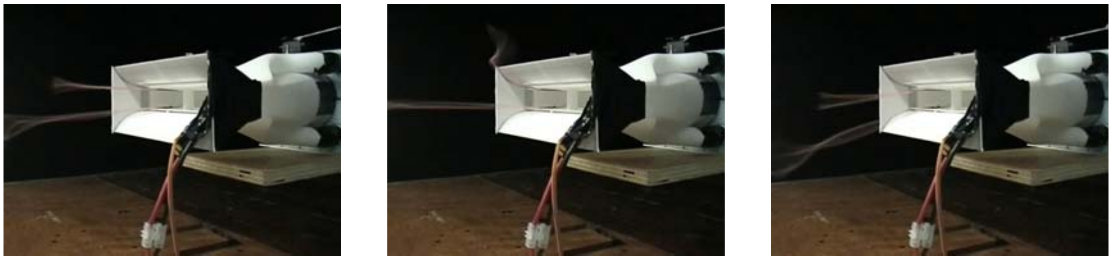

Figure 11. Bench Top Tests of Vector II ABS Nozzle

D. Integrated Demonstrator Aircraft

At the time of writing this report the project was eights weeks from completion and consequently the Integrated Demonstrator was still in the early stages of development. The preliminary design of the aircraft was complete and wind tunnel testing of the first generation design was underway. From experience of the CC and FTV Demonstrators it had been decided that these aircraft, which had successfully been used to convert the flow control technologies into flight hardware, could be further utilised as test platforms for any developments needed for integration of the technologies onto the UCAV planform.

The X45A planform provides a relatively challenging and commercially realistic planform for integration of the flapless controls. This is necessary to enable any potential integration issues to be identified and allow design expertise to be developed. The decision was made to modify the 3-D profile of the fuselage from that of the X45 in order to eliminate the need to redesign an inlet for the new configuration. The X45's dorsal intake was replaced with a pod configuration as shown in Figure 4. This allowed design resources to be targeted at key elements of the project.

A number of design choices were made in order to minimise the risk of the project. Firstly it was decided that the aircraft would make use of conventional controls in addition to the flapless controls. This would enable recovery from any loss of control and would also provide the capability to test the flow control systems in progressive stages. Initially the flow control technologies would be tested during a simple circuit and then extended to include take off and landing manoeuvres. The aircraft would also have detachable fins and a tail plane for initial flight tests. Secondly, the majority of model aircraft are designed with no redundancy. However, the integrated demonstrator has been designed to achieve duplex redundancy by the use of multiple servos and receivers for the conventional and flapless controls.

It was originally anticipated that a number of additional integration issues would be encountered when moving from the FTV and CC Demonstrators to the X45A planform. However, as the Integrated Demonstrator was designed specifically for the FTV and CC systems, it was found that the number of additional design considerations were minimal. Dividing the project into three demonstrators had served its purpose of minimising the project risk by allowing the technologies to be demonstrated independently. The majority of the risk for the Integrated Demonstrator was in developing the platform and not in the flow control systems.

IV. Discussion

A. Elimination of Circulation Control Plenum Chambers

Although widely utilised on experimental test setups, models and aircraft, a major disadvantage of plenum chambers is the space inside the wings that is necessary to accommodate them. On production aircraft, this uneconomical use of space would be unsatisfactory and so a more suitable, yet equally effective solution should ideally be found. One possible solution is to eliminate the plenum chamber completely, instead replacing the unit with a constant area duct with the same slot geometry as with a conventional plenum. A method similar to this is already being used with considerable success on fluidic thrust vectoring systems. Within this duct, straightening vanes could be used to ensure that the velocity profile along the slot was as uniform as possible while minimising internal drag. This would greatly minimise the space requirements for the system, while ensuring acceptable flow conditions. Another possible advantage of this development could be that the system response time is increased. This would be a direct result of having a considerably lower volume of air that would require pressurising before the system reached its optimum operating pressure for suitable flow. However this idea is still at the concept stage with no quantitative results.

B. Future Technologies

The FTV and CC Demonstrators highlighted a number of potential developments to the FTV and CC systems which required further research. These developments included the use of passive control in the FTV system eliminating the need for a secondary air supply and also improvements to the pneumatic power distribution in the CC system. These technologies will have been fully evaluated as part of this six month project and if possible will be implemented on the Integrated Demonstrator. However, the primary aim was to produce a flying integrated aircraft within six months and consequently it was necessary to focus attention on moving the existing technologies from bench top to flight hardware. A recommend plan for future work would include flight testing the evaluated improvements to the FTV and CC technologies and then using an off the shelf autopilot kit to develop the radio controlled Integrated Demonstrator into an autonomous UAV.

V. Conclusions

1) The FTV and CC technologies have been successfully integrated onto a model scale aircraft demonstrating the feasibility of the technologies as flight hardware on a realistic aircraft planform.
2) The world's first aircraft utilising Circulation Control as roll manoeuvre effectors has been flown.
3) A number of implementation issues have been identified including the provision of secondary air supplies, secondary flow ducting and achieving an axis-symmetric to high aspect ratio nozzle. These issues have been resolved before implementation of the technology at full-scale
4) The requirement for an integrated propulsion and flow control system has been identified. The propulsion unit's efficiency and performance would be optimised for operation during provision of the secondary flow for the FTV and CC technologies.

Acknowledgments

The authors thank the following people for their contribution towards this Demonstrator Aircraft project:- Ian Lunnon, Andy Lytton, Phil Geoghegan, Matt Pilmoor, Mario Carrus, Mark Jabbal, Steve Liddle, Luis Garcillan, Gaetan Mabboux.

References

[1] Irvine Ltd – Supplier of Model aircraft and components. www.Irvineltd.com (last visited 13/06/05)
[2]Schubeler – Supplier of model aircraft and components, http://www.schuebeler-jets.de/ (last visited 13/06/05)
[3]Foamwings.co.uk- http://www.foamwings.co.uk (last visited 13/06/05)
[4]Frith, S.P. and Wood, N.J., Investigation of Dual Circulation Control Surfaces for Flight Control
[5] Kennaugh, A., Hobson, D. and Wood, N.J., flow Science Report FS/REPT/0151 – Test on circulation Control Wings, December 2000
[6] Frith, S.P. and Wood, N.J., Effect of Trailing Edge Geometry on a Circulation Control Delta Wing, *AIAA, 21st Applied Aerodynamics Conference, Orlando, Florida, 23rd-26th June 2003*
[7]Mason, M.S., Fluidic thrust vectoring of low observable aircraft, *CEAS Aerospace Research Conference, 10-12 June 2002, Cambridge, UK*
[8]Mason, M.S., Fluidic thrust vectoring for low observable air vehicles, *Journal of the Institute of Mechanical Engineers*