DEVELOPMENT OF A PNEUMATIC SYSTEM TO ENABLE FLIGHT WITHOUT CONVENTIONAL CONTROL SURFACES

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Abstract

This paper describes the design, development, build and preparation for flight test of a unique pneumatic power system to enable flight without the use of conventional control surfaces of the Demon UAV (Unmanned Air Vehicle). It is intended to be a flying demonstrator which achieves pitch and roll control without the use of hinged control surfaces, but instead by using fluidic devices based on the Coanda effect.
The design, manufacturing and testing of the pneumatic power system is discussed as a whole and the key sub-systems; these include: 1) the auxiliary power unit (APU) which is the core of the Pneumatic Power Generation System; 2) the Pneumatic Power Distribution System, which includes ducting and a distribution plenum; 3) the Pneumatic Power Control System, which consists of eight servovalves developed in-house.

1 BACKGROUND

The FLAVIIR[1] project is a five-year research programme looking at technologies for future UAVs and it is funded jointly by BAE Systems and by the Engineering and Physical Sciences Research Council (EPSRC) in the UK. Managed jointly by BAE Systems and Cranfield University, the project includes nine additional collaborating university partners. The research programme covers all essential aspects of aeronautical technology integration for the next generation of advanced UAV/UCAV concepts (Unmanned Combat Air Vehicles). The focus for the research is the “Grand Challenge” proposed by BAE Systems:

> “To develop technologies for maintenance free, low cost UAV without conventional control surfaces and without performance penalty over conventional craft”

The principal goal of this ambitious programme of research is to design, build and fly a small, but representative, UAV embodying the integrated technologies developed in the various research studies comprising the project.

Figure 1: The Demon UAV on the military range.

2 AIR VEHICLE DESCRIPTION

In particular, it is intended to demonstrate the feasibility of total flight control utilizing flapless technologies. In the context of the project, flapless flight control is interpreted to

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[1] Flapless Air Vehicle Integrated Industrial Research. See http://www.flaviir.com

mean circulation control on the wing by means of trailing edge blowing and thrust vectoring the exhaust from the small propulsive gas turbine engine as indicated in Figure 2. Hence, the need for a pneumatic system.

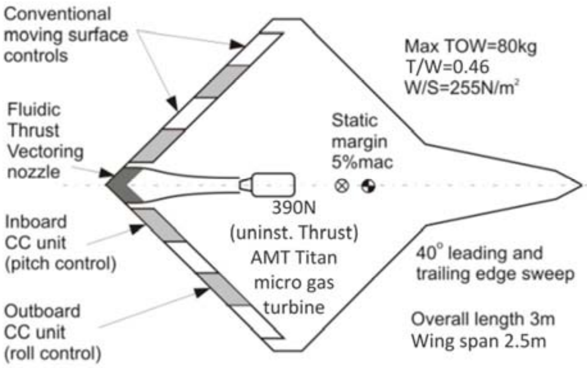

Figure 2. The DEMON UAV showing the location and size of the fluidic manoeuvre effecters.

Demon achieves pitch and roll control without the use of hinged control surfaces, but instead by using fluidic devices and the Coanda effect.
The Demon is the largest flying demonstrator within the FLAVIIR project supported by BAE SYSTEMS and UK Engineering and Physical Sciences Research Council. The Demon has a take-off mass of 80 kg and a diamond shaped wing plan-form of 2.5 metres in span (see also 3-view drawing at the end of the document).

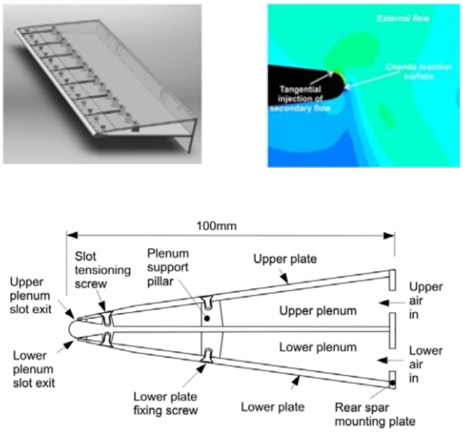

Figure 3: The Circulation Control unit which replaces conventional trailing edge devices [Ref. 10].

The vehicle has provision for fluidic thrust vectoring for pitch control and four circulation control units (two per wing) for roll (an outboard pair) and pitch (an inboard pair) control, as showed in Fig. 2. A conventional rudder is used for yaw control.
How the compressed air is conveyed to the end consumers (Circulation Control units) will be described in the section dedicated to the Pneumatic Power Distribution System. The Pneumatic Power Control System section will then describe how the flow rate is regulated to each slot according to the outputs from the avionics.

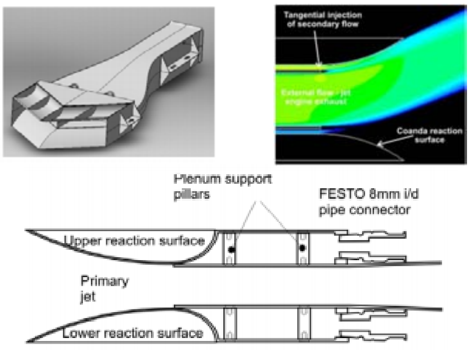

Figure 4: The Fluidic Thrust Vectoring nozzle which provides cruise pitch control [Ref. 10].

The fluidic thrust vectoring pitch control system uses bleed air from Demon's 390 N turbojet main engine. However, during descent and landing neither thrust nor bleed air in large quantities are available, as the thrust setting is low during these flight phases. Thus, the approach taken to ensure fluidic roll and pitch control during all flight phases is achieved is to utilise a dedicated auxiliary power unit to provide pressurised air to the inboard and outboard circulation control slot pairs. This presents a challenging design for a number of reasons, as it will be exposed in the Pneumatic Power Generation System Section.

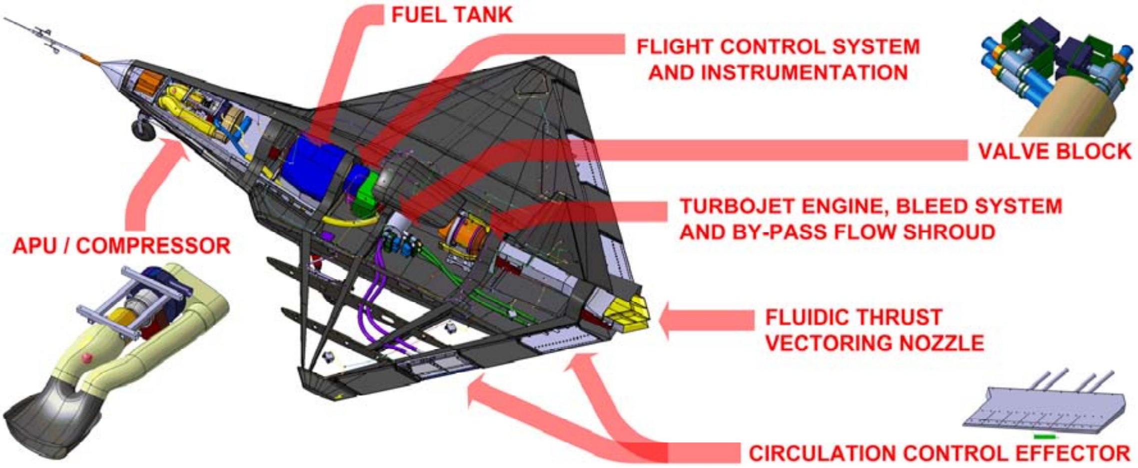

Figure 5: Demon Pneumatic System Components and Layout

3 A NOVEL SYSTEM

The work on the pneumatic power system for the Demon vehicle started with a review of existing designs. The starting point was sought for through the generation of a database of 60 UAV between 45 kg and 450 kg of MTOW.

In fact, the outcome of such a literature review was that simple forms of pneumatic system can be found as part of the braking system or ice protection system, though not intended for generation of secondary power as the Demon case is.

As a result, the authors designed, assembled and characterised through bench testing a novel pneumatic system for Demon UAV, which became flight-ready in November 2009.

The Demon vehicle falls into a class occupying a gap in the market where systems technologies are immature and not well established for aerospace applications. For smaller UAVs than Demon, technology developed for radio-controlled models is directly applicable. While, for larger UAVs technology solutions for manned aircraft may be applied. For vehicles of take-off masses lying between 80kg and 270 kg, existing aircraft systems technologies and approaches are not necessarily applicable (see Fig. 6). Indeed this is certainly the case for a pneumatic system, rarely found on vehicles the size of Demon.

The design approach taken has included the use of commercial off-the-shelf (COTS) products from aerospace and other engineering sector suppliers, customised COTS components, and designed and manufactured from scratch to meet our specifications. At all times the balance was considered to minimise cost and development time.

The result is a unique system able to supply the four circulation control plenums with sufficient mass flow rate at sufficient pressure to achieve fluidic pitch and roll control of the vehicle.

This paper discusses the design, development and flight test processes of the system as a whole and the key sub-systems; these include:

- The auxiliary power unit (APU) which is the core of the **pneumatic power generation system**. It consists of a micro turbojet engine driving a free power turbine, itself driving a compressor capable of delivering air at 90 grams/second at 1.8 bar. This is a unique APU developed for Demon by building on radio-controlled model aircraft engine technology.

- The **pneumatic power distribution system**, including ducting and a distribution plenum delivering hot pressurised air from the APU at the front of the aircraft to four circulation control units at the aft of the aircraft.

The design of this system has been achieved with minimised pressure losses to ensure the required pressure at the circulation control slots' plenums.

- The **pneumatic power control system**, consisting of commercially available electromechanical actuators mounted on and driving customised ball valves.

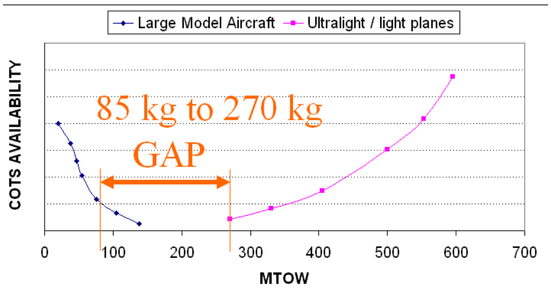

Figure 6: Gap between Large Model Aircraft and Ultralight/light planes COTS sourcing. On the Y axis, the percentage of the adopted COTS components per category, based on the UAV database which was generated.

4 PNEUMATIC POWER GENERATION SYSTEM

4.1 DESCRIPTION

Each CC unit (Circulation Control, as shown in Fig. 3) requires 20 grams/sec of compressed air. The feed pressure has to be between 0.3 barG and 0.5 barG per unit. There are four units to supply, which brings the total required mass flow to 80g/s. The on-board compressor will have to deliver a mass flow rate in excess of such figure at a suitable pressure to compensate the pressure losses along the line and pressurise each of the four units at 0.3 barG to 0.5 barG.

For such operating conditions the most suitable type of rotating machinery proved to be a centrifugal compressor. As to the source of torque to drive such compressor, various solutions were investigated:

1) a geared-up reciprocating two-stroke engine, which would give a high power-to-weight ratio;
2) a geared-up reciprocating Diesel engine, which would share the same fuel as the main turbojet engine (Jet A-1), eliminating then the need for an additional fuel system;
3) a direct-drive electric motor, capable of speed such as 30,000 rpm with no need for a gearbox
4) a direct-drive Wankel engine, in a similar arrangement to the option above, but not as onerous on the batteries;
5) a direct-drive turboshaft.

The last option proved to be the most advantageous compromise between minimum complexity and mass saving, even with its higher fuel penalty (a typical fuel consumption figure for a small turboshaft is 18 grams/hp/min, which is higher than the other internal-combustion engine options). In fact, a turboshaft engine would, of course, burn Jet A-1 fuel and be supplied by a simple extension of the existing fuel system.

The mass budget for such an Auxiliary Power Unit was 2 kg and it had to be within a 4 dm^3 volume (130mm-diam cylinder by 300 mm of length).

Unfortunately, a market investigation revealed that no suitable turboshaft engine was available.

The authors liaised then with Wren Turbines Ltd[2] and an initial feasibility study gave encouraging results. The outcome was turning a micro turbojet unit into a turboshaft by adding a free turbine, in a reverse-flow fashion to minimise the length of the power shaft. Such a unit was rated at 5.62KW (7.5hp). It was subsequently coupled with a modified automotive centrifugal compressor (turned-down Garret impeller, custom-made diffuser & casing). The final overall mass of the unit was 1.85 kg.

Once built, an extensive testing campaign lay ahead. As often happens when a component is custom-made, both the customer and the designer are aware of the features of the

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[2] See http://wrenturbines.co.uk/home

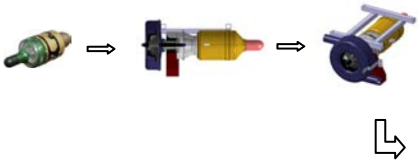


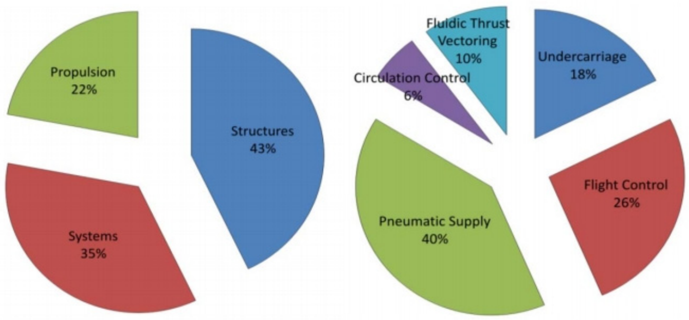
Figure 7: From the COTS micro turbojet engine to the final miniature APU.

product, and its limitations. These very limitations, though, need exploring and discovering whenever dealing with COTS components, most of time starting from a black-box approach.

Unless an independent testing organization obtains the original vendor data for assurance testing, the testing campaign is substantially more demanding when dealing with modified COTS components rather than custom-made ones. This originates from the fact that the use one makes of a COTS part is often very distant from its designer's intentions, and actually more properly one is abusing rather than using the COTS part; but this is implicit in the concept of exploiting COTS components. For this very reason the testing campaign is to be more vast and deeper than for custom-made solutions.

From some preliminary energy-balance calculations, it was found that the highest achievable pressure at the required mass flow rate and given power, was approximately 0.8 barG. Which left some 0.5 bar as a pressure-loss budget. An extremely low-loss distribution system was clearly paramount.

A further feasibility study revealed that an extra-low-loss distribution system was actually achievable. Key features would have been super-finish ducting and an optimised valve-block/plenum design.



a) DEMON weight breakdown *b) DEMON systems weight breakdown*

Figure 8: Weight impact of fluidic effecters on system weight [Ref. 10].

Large-bore tubing and valves were the obvious starting point, but a trade-off with mass budget was paramount. Especially if it is pointed out that the 35% of Demon mass is represented by systems, the 40% of which is the Pneumatic Power System alone (see Fig. 8).

Finally, at least, the authors knew what to design to: 80g/s at 0.8 barG. Subsequently, the custom-made vanes in the diffuser were machined to meet these figures. After testing, the unit proved to be capable of delivery 90 g/s at 0.8 barG, as described in the following section. These figures were the starting point for the design of the Pneumatic Power Distribution System.

4.2 TESTING

The testing campaign of the Demon APU consisted of three phases which are hereinafter described. The rig which was used for all three phases is shown in Fig. 10. Two rotameters (vertical flowmeters, drag-vs-gravity principle) were fitted at suitable distance from the compressor-outlet elbows (visible in Fig. 10, copper made). The flow rate was directly readable in m^3/s. Each of the two metering columns was fitted with a temperature probe sensing the air temperature just before the rotameter. This feature was introduced to allow for air density correction, as the generated compressed air is approximately between 60°C and 80°C, according to the throttle setting and pressure. Each column had three pressure sensors at strategic stations in order to read the air pressure inside the rotameter and to take into account pressure losses along the line. At the top of the columns, two large-bore, plastic-made ball valves acted as variable restrictors, allowing for backpressure adjustment. In other words, by varying the restriction at the end of the line, it was possible to test the unit under different load conditions.

Phase 1: The first phase in the testing campaign of the Demon APU was the generation of a compressor map. This was done by increasing the load on the compressor and by making it surge at various throttle settings. The load valves were gradually closed and increased was the backpressure exerted on the compressor outlets, until the compressor surged. Results can be seen in Fig. 9. The relevant working points for the Demon case are two:

- Max Pressure Delivery = 0.8 barG @ 90 gr/sec;
- Max Flow Rate Delivery = 130 gr/sec @ 0.6 barG.

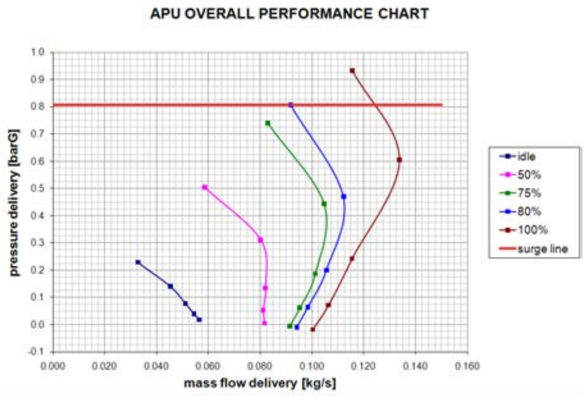


Figure 9: The APU compressor map.

Phase 2: Asymmetric load test. This test was carried out to assess how overall performance decreases when there is a non-negligible pressure difference between the left and right outlet of the compressor diffuser. The authors opted for a double-volute, vaned diffuser as it tends to be more accurately reproducible in a miniature design, hence achieving higher efficiency than a single-volute, vaneless diffuser. Conversely, if in one of the two volutes the pressure builds significantly up due to, e.g., a downstream restriction, the whole flow becomes biased to the other volute resulting in higher losses. The bigger the internal volume of the diffuser itself, the more such a compressor can tolerate asymmetric loading without affecting the overall performance. In other words, the diffuser itself can act as a settling chamber, or plenum.

The left and right outlets of the Demon APU had to supply respectively the port and starboard branches of the Pneumatic Power Distribution System. Each branch feeds one inboard CC unit (for pitch control) and one outboard CC unit (for roll control). This means that between port and starboard there can be a difference of 50% in terms of required mass flow rate. Which equates to a 50% restriction when one unit only is being used on one side and two units are begin used on the other.

Therefore, to understand whether a single, joined plenum of greater capacity was needed in parallel along the line, the asymmetric load test was performed by gradually closing only one of the two load valves at a time.

Such a bench test showed that the APU as a stand-alone could tolerate up to approximately 15% asymmetric loading before suffering from significant losses. In other words, under a 15% left/right asymmetric load, the pressure and flow rate figures delivered by the APU became border-line for Demon application, being they respectively 0.76 barG and 80 g/s. It is reminded that the minimum requirements were 0.8 barG and 80 g/s and that the APU delivery figures in condition of symmetrical load were 0.8 barG and 90 g/s.

As a result, the authors made provision for an additional in-parallel plenum, which had to be sized and located underneath the main engine air intake. This can be seen in Fig. 12, approximately in the centre of the vehicle. The plenum sizing procedure is described in the Pneumatic Power Distribution System section.

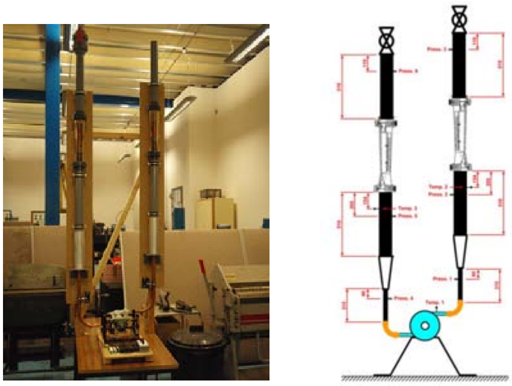


Figure 10: The APU bench-test rig.

Phase 3: The third phase in the testing campaign of the Demon APU was aimed to assess the performance of its air intake system.

As it can be seen from Fig. 7, the APU needs air feeding through both its ends: on the front end we have the gas generator intake and on the rear end the driven compressor intake. This is due to the fact that the micro turbojet unit was turned into a turboshaft by adding a free turbine, in a reverse-flow fashion to minimise the length of the power shaft.

Such an arrangement proved to be ideal in term of vibration but added some complexity to the air intake system. The APU had to be placed in the nose bay for centre-of-gravity reasons. Provision for a chin-scoop ram intake had already been made on the vehicle, but from there two options lay ahead:

1) Design an air induction system based on two separate ducts, as it can be seen in the bottom left corner of Fig. 5. Such an arrangement was recommended by Wren Turbine Ltd, the APU manufacturer;
2) Both the gas generator and the driven compressor sucking from the same chamber. Namely the whole nose bay of the aircraft would act as a plenum.

In both cases ram pressure would help, but it was decided not to plan on it, since it would give an extra 3% with respect to the ambient pressure at the typical cruise speed of the vehicle (110 kt) in a best-case scenario. As a consequence, ram effect was not part of the testing.

It was decided to proceed with testing solution 2) first, since it was the preferred way forward in terms of costs and mass implications.

A wooden box was therefore designed to enclose the APU and recreate representative conditions of the Demon nose bay (see Fig. 11).

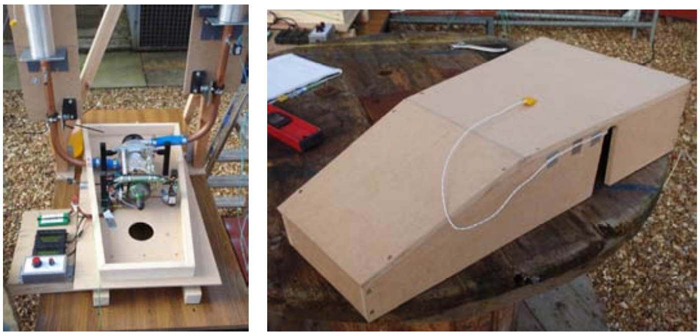


Figure 11: The APU enclosed in the dummy Demon nose bay

The box was sized by using CATIA to match the Demon nose bay volume and its cross-sectional area in four stations along the longitudinal axis. In correspondence to the position of the chin-scoop ram intake on the vehicle, a circular cut-out was made through the bottom wall of the box. The area of such a circular cut-out matched the cross-sectional area of the chin-scoop ram intake.

The test showed that, once enclosed, the APU performs as follows:

- -1.5% in conditions of Max Pressure Delivery, which corresponds to 0.78^+ barG @ 90 g/s (unenclosed, it was 0.8 barG @ 90 g/s);
- -3% in conditions of Max Flow Rate Delivery, which means 126 g/s @ 0.6 barG (unenclosed, it was 130 g/s @ 0.6 barG).

Such performances were judged still compatible with the aforementioned minimum requirements. Hence the decision was taken to accept these reasonable penalties and save extra mass and complexity by doing without the separately-ducted air induction system.

5 PNEUMATIC POWER DISTRIBUTION AND CONTROL SYSTEMS

5.1 DESCRIPTION OF THE PNEUMATIC POWER DISTRIBUTION SYSTEM

The Pneumatic Power Distribution System routes pressurised air from the APU sub-system to the CC units, which are the end users of the compressed air. Because of the very limited margin on pressure delivery given by the APU, an extremely low-loss distribution system became paramount. In fact, once working enclosed in the nose bay, the APU only delivers a maximum of 0.78^+ barG @ 90 g/s. It has to pressurise each of the four units at 0.3 barG to 0.5 barG, which leaves just 0.5 bar as a best-case pressure-loss budget.

An initial feasibility study revealed that an extra-low-loss distribution system was actually achievable. The authors began a market investigation to source suitable COTS

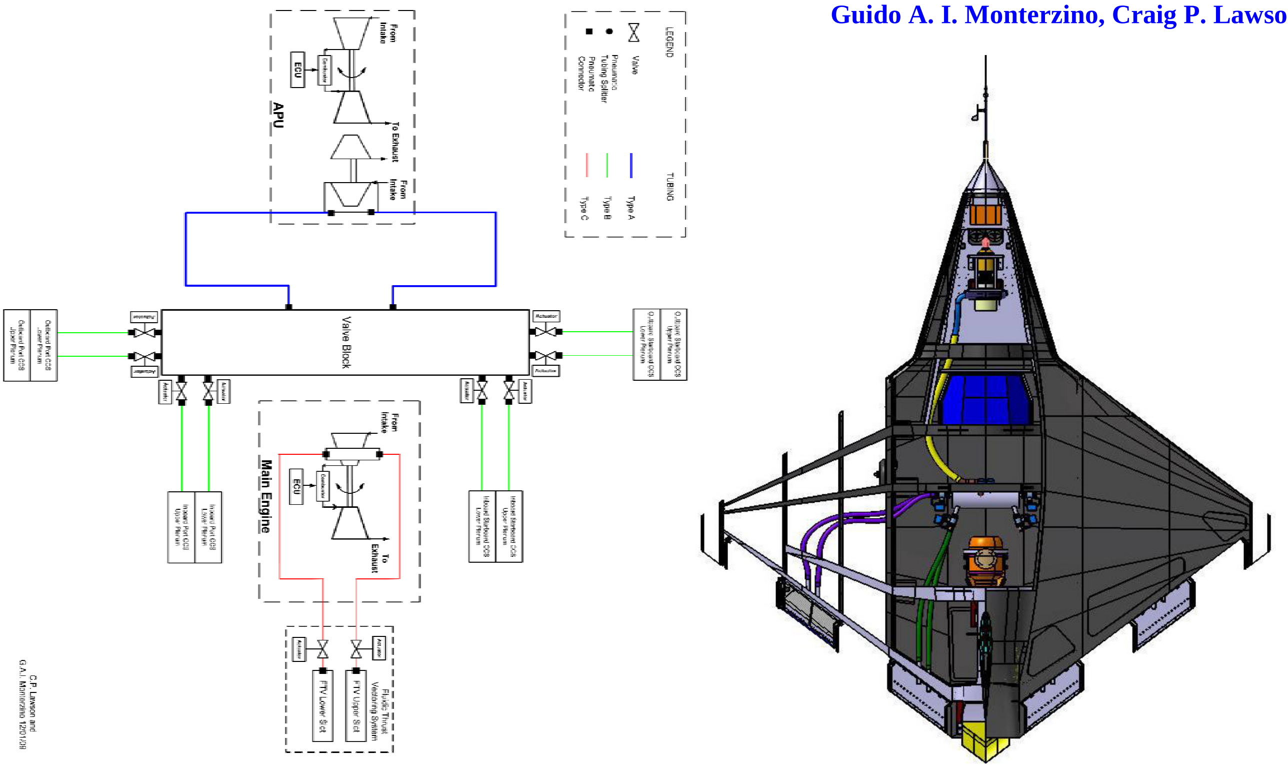


Figure 12: The Pneumatic Power Distribution System on the Demon UAV; schematics and plan view from the digital mock-up

(Commercial Off-The-Shelf) components. Maximising the use of COTS parts was one of the aims of FLAVIIR, in order to minimise development costs, achieve rapid implementation of the envisaged solutions and to prove that mission-critical systems and COTS-based design are nowadays compatible.

Suitable components would have had to feature a super-finished inside surface in the case of the ducting, as well as a small minimum bending radius. It would have had to have a large inner bore in the case of valves and fittings, and so on. At the same time, the preferred materials would have had to be lightweight engineering plastics or aluminium, as a trade-off with mass budget was paramount.

The segment of UAVs between 45 kg and 450 kg of MTOW is very interesting because it contains a gap between two not completely overlapping sources of COTS components (see graph in Figure 6). The lower-end group up to approximately 85 kg of MTOW is reasonably covered by Large Model-Aircraft components, the upper-end from 270 kg to 450 kg is broadly covered by Ultralight (LSA) or kitplane suppliers or even by General-Aviation light-aircraft suppliers. That which sits in the middle is scarcely covered by COTS market. A database of 60 UAVs between 45 kg and 450 kg of MTOW was generated and studied. While analysing the database, sourcing off-the-shelf components for the weight classes coincidental with the identified gap proved to be really challenging.

The currently viable alternatives are either sourcing COTS components from the Large Model-Aircraft market accepting some limitations, or helping oneself to the light plane shelf accepting over-the-top specs, weights and prices: in other words putting together something far from being optimised.

To give an example of the methodology that was used to work efficiently in such a gap, the technical features of the Type-A tubing (see Fig. 12) are listed hereinafter. The Type-A lines deliver the pressurised air to the downstream CC-control valves (elsewhere also referred to as “valve block”, which is described in the Pneumatic Power Control System section of this document). The Type-A tubing was sourced from the food-processing industry, and it proved to be a very suitable COTS component for the Demon Pneumatic Power Distribution System.

Type-A Tubing:
Material: Flexible, hi-purity PTFE
Min Bending Radius @20°C: 325 mm
Outside Diameter: 29.5 mm
Internal Diameter: 26 mm (CSA 531 mm^2)

Mass, Linear: 0.336 kg/m
Length, Overall: 2.18 m
Mass, Overall: 0.736 kg
Temperature tolerance at deliv. pressure: 533 K
Max Operating Pressure, absolute: 5bar @293K

Conversely, the Type-B tubing which was used on the Demon vehicle from the valve block to the CC units, came from the refrigeration industry. Its material, Nylon, presents the same excellent surface finish as the PTFE-made Type-A, but with half the density.

Type-B Tubing:
Material: Flexible, hi-purity Nylon
Min Bending Radius @20°C: 150 mm
Outside Diameter: 20 mm
Internal Diameter: 16 mm (CSA 201 mm^2)
Mass, Linear: 0.130 kg/m
Length, Overall: 6.25 m
Mass, Overall: 0.810 kg
Temperature tolerance at deliv. pressure: 343 K
Max Operat. Pressure, absolute:13.5bar @293 K

Last, two elbow-shaped, 25mm-ID silicon rubber hoses (one per APU outlet) act as connectors between the compressor outlets and the two main Type-A lines by simply stretching over. These components came from the automotive industry and are entirely “COTS” except for the fact that were custom thermo-shaped by the supplier to meet our requirements. Anywhere else along the distribution lines, connections between flexible pipes and metallic components is achieved by overlapping and clamping with jubilee-fashion clips, eliminating the need for traditional connectors.

5.2 DESCRIPTION OF THE PNEUMATIC POWER CONTROL SYSTEM

The core of the Pneumatic Power Control System is the Valve Block. It feeds both port and starboard distribution lines. It is located on the centreline of the vehicle under the main engine intake. The block consists of a 100mm-by-350mm aluminium canister which eight ½” ball valves screw to. Such canister (see Fig. 13) acts as a plenum manifold and it is fed by Type A tubing coming from the APU compressor casing (one tube per outlet). Each ball valve is operated by an independent servo.

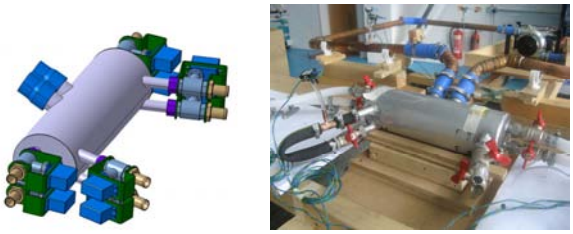


Figure 13: The Valve Block, core of the Pneumatic Power Control System of the Demon UAV.

Mass of valve block, Overall: 3.48 kg (actuators and actuation mechanism included)
Location: between 3rd and 4th bulkhead, under the main intake S-duct
Temperature tolerance at delivery pressure: 403 K (ball valve limit)
Design Burst Pressure (absolute): 6 bar

The Valve Block was structurally sized as a pressure vessel through ESDU datasheets. Conversely, the fluid dynamic sizing had to be based entirely on departmental experience, as a parametrical, ESDU-style sizing procedure for plenums could not be found. There seem to be a lack of literature on this area. More and more often, the alternative is a CFD study, which was not compatible with the development tempo of the Demon UAV. The ironbird testing campaign eventually proved the internal volume of 2.7 dm^3 to be sufficient to achieve the desired plenum behaviour. In other words, three goals were achieved:

1. Allow for deep mixing of the two feeds coming from the two compressor outlets;
2. Keep asymmetrical load between left and right compressor outlets well within 15%;
3. Damp pressure fluctuations in pre-surge conditions.

The canister was custom made by BAE Systems through TIG aluminium welding, whereas all the other valve block components were of COTS origin. A carbon composite version of the canister was also considered. The eight servovalves (see Fig. 14) were developed in-house, starting from modified-COTS valves and modified-COTS servos.

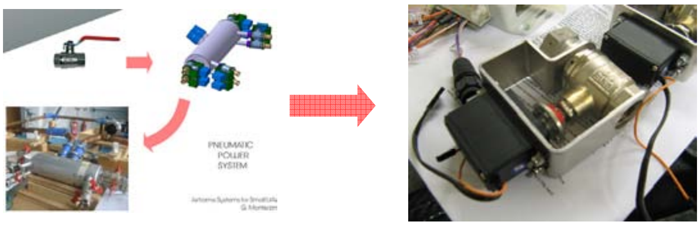


Figure 14: The valve block of the Pneumatic Power Control System, and a close-up of one of the eight servovalves.

5.3 TESTING

An ironbird dedicated to the Pneumatic Power System of the Demon UAV was built to test the three pneumatic subsystems, which have been described so far, all together to a higher integration level (see Fig. 15).

The design phase of the ironbird was preceded by a Matlab simulation aimed to giving the authors a quantitative understanding of the pressure losses along the whole system. The input numbers and coefficients reflected the actual materials as much as possible (Nylon-made 16mm-ID Type-B tubing, cast brass 15mm-ID ball valves, etc). The simulation was also used in the sizing procedure of the dummy copper line which had to replace the Type-A tubing on the ironbird. In fact, a PTFE line would have proved to be a real challenge in terms of pressure tapping, due to the fact that bonding and brazing are obviously not available options on PTFE. Therefore the total amount of losses along the dummy copper line (28mm ID) had to be the same as the PTFE case (26mm ID). The simulation helped to adjust the pipework length to match the pressure loss, having as inputs the diameter mismatch and the different inside surface finish. The Type-B tubing was actually implemented in the ironbird. Up to 8 pressure tapping stations could were simultaneously read and logged through a data acquisition system; and up to 5 temperature stations. No flowmeters were fitted as the APU had been fully characterised as a stand-alone, which made it possible to have a fairly reliable estimate of the delivered mass flow rate at any given moment.

Phase 1: Ironbird Mk1, fitted with a dummy valve block and with port side only of the Pneumatic Distribution System. This was done in a very early stage, while awaiting the delivery of the real valve block. However, this allowed to validate the Matlab simulation and to assess the behaviour of CC unit when supplied by the APU, as such units had always been previously fed by a stationary compressor.

Phase 2: Ironbird Mk2, fitted with the real valve block and the whole of the Demon Pneumatic Distribution System. Two CC units could be fed at a time, permitting interesting surge-oriented investigations. This also made it possible to assess the behaviour of the valve-block plenum itself in terms of mixing efficiency and pressure fluctuation damping.

Phase 3: The main components of the Pneumatic Distribution System were ‘transplanted’ from the Ironbird into the Demon vehicle (except for the copper line). The valve block servovalves were electrically operated for the first time. This allowed testing activities at an even higher level of integration, until the system reached the actual “flight-ready” standard.

On the whole, thanks to Ironbird the Pneumatic Power System of the Demon UAV was fully characterised. This includes pre-surge and post-surge behaviours, on which areas the postprocessing is still on-going.

Moreover, the Ironbird-based tests eventually confirmed most of the predicted pressure loss figures.

In condition of maximum throttle setting and maximum pressure delivery, the typical pressure values are as follows:

- At compressor outlets: 0.78 barG
- Inside valve block: 0.60 barG
- Inside CC units: 0.33 barG to 0.45 barG

Figure 11: The Ironbird for the Demon Pneumatic Power System. From left to right: design phase, Mk1 and Mk2.

6 CONCLUSIONS

The research and development reported in this paper has resulted in a flight-ready pneumatic power generation and distribution system being developed. This has paved the way for the potential flight of the Demon UAV using fluidic controls in place of conventional hinged surfaces for both roll and pitch control.

The pneumatic systems reported are novel, particularly applied to this scale of vehicle. This has resulted in a design approach characterised by the use of a mixture of COTS, customised COTS and bespoke components, and the extensive systems design, integration and testing associated with this approach.

The performance of the pneumatic power generation systems has been reported in detail. The characteristics of the pneumatic power distribution system are covered. The detailed performance of this system is the subject of further scientific testing.

Additional further work could involve gathering and analysing flight test data on the performance of the systems described in this paper.

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APPENDIX A: DEMON THREE VIEW DRAWING