COMPARISON OF FUEL BURN AND NOISE CHARACTERISTICS OF NOVEL AIRCRAFT CONFIGURATIONS

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Abstract

The paper will introduce the drivers that are encouraging the development of environmentally benign aircraft.

It will describe investigations of aircraft designed to tackle broad environmental issues, particularly for aiming to reduce fuel burn, and its consequent pollutants.

The paper will continue with a description of a study of the conceptual design of a range of commercial aircraft. They have been optimized for design ranges of 4,000 or 8,000 n miles, with a payload of 270 passengers and common field length requirements. All variants share a common fuselage layout and use consistent design methods. Each range category will contain the following configurations.

- *Conventional twin-engine aircraft*
- *High aspect ratio, rear engine*
- *Box wing*

Comparisons will be made of aircraft dimensions, masses, fuel burn, noise, acquisition and direct operating costs.

Descriptions will be given of detailed group design projects that have been performed for three of these configurations.

The paper will conclude with recommendations for further development of these and other aircraft configurations.

Nomenclature

b	Wing span
CAA	Civil Aviation Authority
CO_2	Carbon Dioxide
DOC	Direct Operating Costs
D_{min}	Minimum distance to receiver
$\triangle$	Flap deflection angle
ECAC	European civil aviation conference
EPNL	Effective perceived noise level
EPNdB	Measurement of EPNL
ESDUPAC	ESDU noise pack
FO	Flyover measurement point
ICAO	International Aviation Civil Organisation
G8	Group of eight economic nations
IATA	International Air Transport association
L_A	A-Tone corrected sound levels
LD3	Standard underfloor cargo container
λ	Length of the flight path segment in ECAC methodology
$\wedge$	Lateral attenuation factor
Δ_v	Duration correction factor
Δ_I	Installation correction factor
Θ	Polar angle of emission
MIT	Massachusetts Institute of Technology
Noy	unit for noise annoyance
N	Newton
NPD	Noise Power Distance
P	Acoustic pressure (Pa)
r	distance from noise measurement point
OASPL	Overall sound pressure level
OFX, ONX	Engine performance prediction tools (Ref. 9)
PNLT	Tone corrected perceived noise level
S	Gross wing area
SPL	Sound Pressure Level (dB)
Sr	Strouhal number
t	time

TURBOMATCH Cranfield University engine performance prediction tool
V Aircraft velocity
USG United States Gallons

1 Introduction

The impact of aviation on the environment has been of growing concern for several decades. Significant steps are required to alleviate aircraft emissions in a generally growing air-transport market.

A major initiative was taken in Europe in 2001 with the publication of quantified targets. These were summarized in Ref. 1 as:- "Europe…has it's Advisory Council for Aeronautical Research in Europe (ACARE), which, in 2001 committed the industry to develop technologies that would cut CO_2 by 50% per passenger kilometre, cut NO_X by 80% and halve perceived noise levels by 2020, relative to 2000 standards".

Such large reductions not only require new technologies and operating techniques, but will also need alternative aircraft and engine configurations. This paper will concentrate on a number of novel aircraft configurations or operating concepts and will compare the results with conventional baseline aircraft, using consistent methods.

Several of the conceptual designs have been taken to the preliminary stage by means of extensive group design projects, which will also be described.

2 Background

2.1 Individual Research Projects

All Cranfield University students of the MSc in Aerospace Vehicle Design perform both individual and group projects.

In the current study, Monborgne (Ref. 2) and Krebs (Ref. 3) conducted individual conceptual designs of aircraft optimized for ranges of 4,000n.m and 8,000n.m, respectively. Nguyen (Ref. 4) produced a noise prediction methodology, suitable for aircraft conceptual design, which was used for a number of configurations in the study.

2.2 Group Design Projects

Cranfield University has used Industry-class Group Design Projects (GDP), since its foundation, as a means of combining advanced education and applied research into new aircraft concepts.

The GDPs allow significant in-depth design solutions at conceptual, preliminary and detail design stages. More than 50 graduate students per GDP are allocated responsibility for preliminary/detail designs of major parts of the aircraft such as the forward fuselage, a flying control surface or an airframe system such as fuel, environmental control, propulsion, landing gear, avionics or the control system. Further topics include performance, cost, reliability and maintainability. This allows much more realistic estimates to be made of mass and performance and demonstrates that the construction and system design methods are feasible.

These 8-month programmes, using industry-standard design tools and methods, are supervised by more than 10 faculty staff and operate it what is termed as a 'virtual industrial environment'.

2.3 Environmental Issues

Environmental concerns have been key drivers for the aerospace industry for several decades. Although air transport produced only 2% of the CO2 emissions in 2000, several targets were set by the aviation industry in accordance with the G8 requirements in 2009, including carbon neutral growth by 2020 and continuing the ACARE targets mentioned in Para. 1.

The consistent growth of air transport over many years has added further pressure to reduce aircraft-related pollution.

Ref. 2 stated that: 'In 2025, the International Air Transport Association (IATA) and the International Civil Aviation Organisation (ICAO) forecast that 4.5 billion passengers and 110 million tons of cargo will travel by plane. This means some 46,000 aircraft will be in the air and at current fuel consumption. This would lead to an annual fuel consumption of 128 billion U. S. gallons'.

Aircraft noise has been the most noticeable environmental effect and has been subject to increasingly stringent noise regulations, but again, significant improvements will be required in future.

3 Fuel Burn and Noise Comparison Study

3.1 Aircraft Requirements

These were chosen to be consistent with those chosen for the Cambridge University/M.I.T. Silent Aircraft Initiative. Ref. 5 describes parallel work done at Cranfield University to produce engine and aircraft concepts designed to the same requirements. Those concepts used reduced noise as the dominant requirement, but a more balanced set of requirements was chosen for the current study and thus only the non-noise requirements were used. Refs. 5 and 6 give full descriptions of the resulting broad delta aircraft, and will not be repeated here.

The study objectives were to compare the fuel performance, noise and the operating cost of 3 different types of airframe configurations.

The cardinal points of the requirements were:-

- Payload – 250 passengers in a three class arrangement or 23,750 KG payload but 35150 KG maximum payload
- Cruse Mach no. of 0.8
- Ranges 4,000 or 8,000 n. miles with international reserves.
- Balanced field length of 2900 m, under I.S.A, sea level conditions.

3.2 Design Constraints

The aircraft were to be designed to meet FAR and EASA part 25 airworthiness requirements. A common fuselage was chosen to accommodate the specific number of passengers and had a total length of 57m and a width of 5.64m. The chosen width is similar to the one the A330 that allows the use of two LD3 containers abreast in the cargo compartment.

The study assumed that 50% of the aircraft structures would use carbon fibre composite construction, have modern systems and engines in the class of the Rolls Royce Trent 1000/X3/CFM GEN-X families with a typical cruise specific fuel consumption of 0.48 N/N/h. Fuel costs were assumed to be $2 US per US gallon and aircraft annual utilisation of 4,500 hours.

Four aircraft concepts were chosen for comparison, to reflect the concepts which had been previously designed at the preliminary level by means of Cranfield University Group Design Projects. These were:-

1. Baseline aircraft using conventional configurations designed for this study to the above requirements.
2. Conventional configuration aircraft which achieves 8,000 n. miles range by the use of civil flight refuelling –the MRT7-3 Meridian (Ref. 7).
3. Natural laminar flow configuration – the A-6 Greenliner (Ref. 8).
4. Box-wing airliner – the A-9 (Ref. 10).

The above aircraft were not all designed to identical requirements, so the current study made modifications to the designs to make them consistent.

3.3 Design Process

Fig. 1. shows the design methodology used for all the concepts.

This methodology was developed by two students described in Ref. 2 and 3. Each student was assigned to design particular spreadsheets and the work was shared.

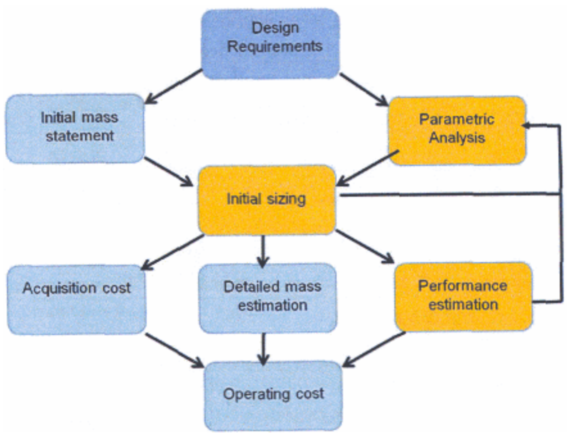

Fig. 1. Methodology diagram

Ref. 4 describes the parallel work done to develop a conceptual prediction methodology for airframe and engine noise.

Given the design specifications, the first estimations of mass were made, followed by the first parametric analyses in order to have an idea of thrust to weight ratio and wing loading for the aircraft that were being designed.

This allowed the running of the spreadsheet of initial sizing, where the raw geometry of the aircraft was determined. The process was then iterated to refine geometry to have the best drag value and to remain in the requirements of the parametric analysis.

The second step was to refine the mass estimation and centre of gravity locations. The refined mass estimation allowed the use of the acquisition cost method to have an idea of the price of each aircraft. The mass of the aircraft and the drag estimation then allowed the use of performance spreadsheets to produce the fuel performance for each concept.

The spreadsheets were then iterated to refine the geometry, the mass in order to optimize the fuel performance of the aircraft.

The final step was to run the Direct Operating Cost spreadsheet. This last step allowed the final comparison of fuel performance against operating cost.

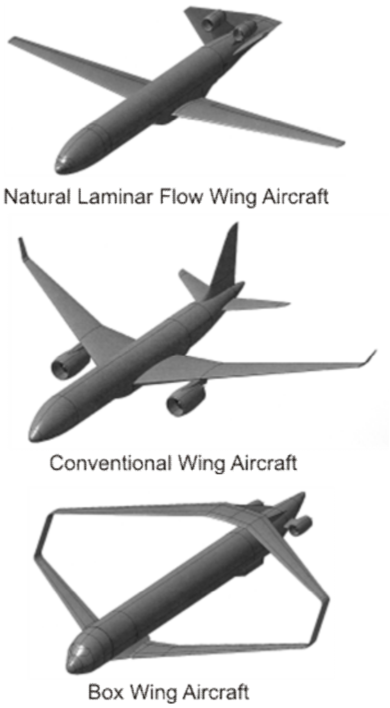

Fig. 2. CAD Models of the comparison study aircraft

Fig. 2. shows CAD models of the resulting conventional, natural laminar flow and box-wing aircraft.

3.4 Comparison Study Results

3.4.1 Fuel burn versus direct operating costs (doc) for 4,000nm aircraft

- The unit chosen to represent fuel performance was the US gallon per passenger and per block hour. This was chosen because one of the ACARE objectives was given in this unit.

  U.S. cents per available seat mile were chosen as units to characterize direct operating cost performance. Figure 3 gives the comparison of DOC and fuel performance for different aircraft; all calculations using the methods outlined in Refs. 2 & 3. The main results of the 4,000n mile and 8,000n mile aircraft are also summarised in Table 1.

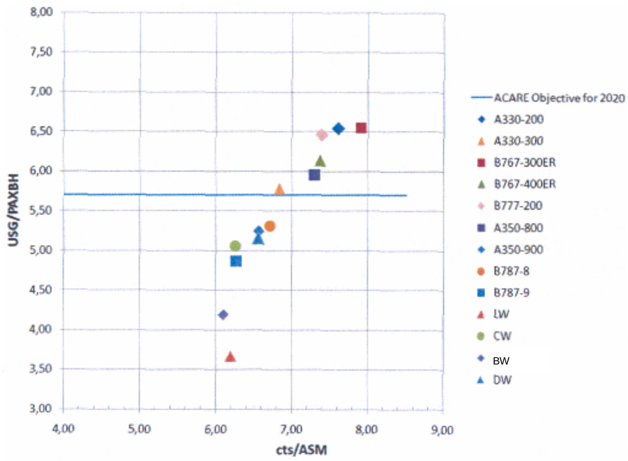

Fig. 3. Fuel performance vs DOC – 4000nm

Several comments may be made about Fig. 3.:- The conventional wing design (CW) aircraft can bring about 19% fuel burn improvements compared with current existing aircraft while it can bring 15% improvements in the direct operating cost. The conventional wing design also brings improvements compared with next generation aircraft such as the A350 and B787. More precisely, the fuel performance of our conventional wing design aircraft is some 4% better whilst the operating costs are 5% better. This is due to the fact that our aircraft were specifically designed for this range, while A350 and B787 have been optimized for longer ranges.

- The Box Wing (BW) aircraft was a surprise because, as expected, the fuel performance of the aircraft was better than the conventional wing design but the operating costs of the box wing aircraft were also better. Even if the acquisition price of the aircraft is high, the fuel saved helps to counterbalance the higher acquisition price of the aircraft, resulting in an operating cost of 3% better than our conventional wing design. Fuel burn and DOCs savings relative to current aircraft were some 33% and 18% respectively. The new aircraft however, had more advanced engines, systems and structural technology.
- The best compromise between operating cost and fuel burn performance was given by the laminar flow wing aircraft (LW). This aircraft has an outstanding fuel burn performance of 3.67 USG/pax/BH, some 23% better than the conventional wing aircraft fuel performance. However, the laminar wing aircraft flies at slower speed implying that this aircraft will need more time to perform a 4,000nm mission, reflected in the operating costs.
- Civil flight refuelling was not appropriate for a 4,000nm range, and was not studied here.

3.4.2 Fuel burn versus direct operating costs (doc) for 8,000nm aircraft

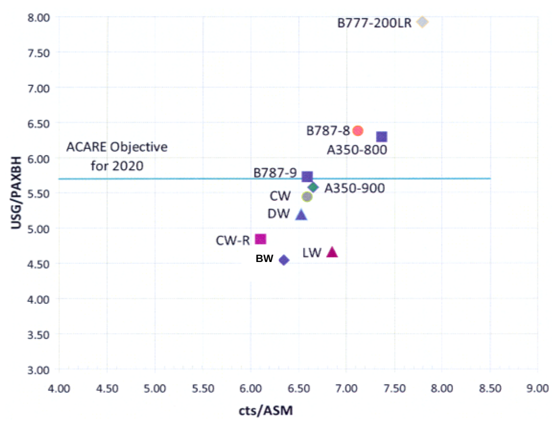

Fig. 4. Fuel performance vs DOC – 8000nm

Range	Aircraft Type	% Fuel Burn Saving	% DOC Saving
4,000n m Range	Average current medium range	0	0
	787/A350 class medium range	15%	9%
	Conventional Wing (CW)	19%	15%
	Box Wing (BW)	33%	18%
	Laminar Wing (LW)	42%	16%
8,000n m Range	Current long range	0	0
	787/A350 class long range	28%	15%
	Conventional Wing (CW)	31%	15%
	Conventional Wing-Refuelled (CW-R)	39%	21%
	Box Wing (BW)	42%	19%
	Laminar Wing (LW)	42%	13%

Table 1. Fuel Burn Comparisons

Some comments are given below about Fig. 4., and Table 1, which summarise relative fuel burn and operating costs:-

1. <u>The conventional wing (CW) design</u> offers some 30% fuel savings and 15% cost savings relative to currently-operating, larger aircraft. Fuel and cost savings relative to the Boeing 787-9 and Airbus A350-900 predictions are relatively small and within possible error-bands of the simple analysis methods used.
   The flight-refuelled aircraft, CW-R is sized for a 4,000nm cruise and is then refuelled at this point to obtain the full 8,000nm range. Suitable penalties were calculated for the fuel system modifications required to receive fuel from a boom, and for suitable fuel reserves.
   The results shown in Fig. 4. indicate a fuel saving of some 39% and cost savings of 21% relative to the predictions of current long-range design.

2. <u>Laminar Wing</u> The results for the LW with its laminar wing indicates that it is some 3% more expensive than the baseline CW aircraft due to its lower speed and hence the following higher crew cost and fewer flight cycles per year. Another disadvantage might be the size of the crew which is needed for one flight. It was assumed in the analysis of all aircraft that four pilots are required for an 8,000nm flight. Due to the extra flight time of 2.3 hours, there might be a bigger crew required. The fuel savings,

however, promise some 42% savings, relative to current aircraft.

3. Box Wing There is considerable technical risk with this aircraft (BW), but it offers some 17% fuel burn and 5% cost improvements relative to the baseline CW aircraft and some 42% and 19% relative to current aircraft. It is suggested that this is further studied.

3.4.3 Conceptual Design Noise Prediction Goal

Ref. 3 describes the development of an empirical and semi-empirical noise prediction tool for use at the aircraft conceptual design phase. Fig. 5. shows a flowchart of the latter approach.

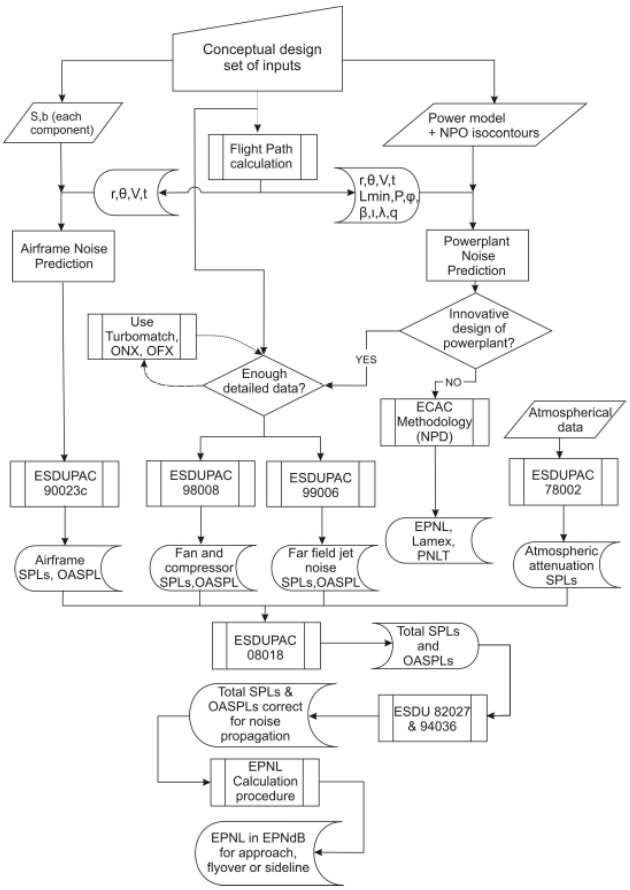

Fig. 5. Noise prediction method structure

The structure is quite linear. It starts with inputs resulting from previous conceptual design steps and provides a single value in EPNL for given certification points, the constraint function. As can be seen, the performance module feeds several other modules and was developed first in order to test the good functioning of the noise prediction modules.

The modules have been implemented as they constitute the core of the tool. Secondary modules will be developed in future as they bring some substantial correction to the SPLs in some cases (side-line measurement point, for instance).

The use of Turbomatch, ONX and OFX engine performance was used in order to feed ESDUPACS 98008 and 99006.

A validation test was achieved with two aircraft (B767-200 and A320-200) with close results (0.4-0.8 EPNdB) for the approach point. This showed that the program was correctly written and linkages between modules were successful.

An application to the 8,000nm Laminar Flow conceptual design was also done with a result of 99.94 EPNdB at the approach point (worst case). This seems quite high compared to current technology but might be explained by the sizing and deflection values of the flaps. A possible optimisation is required.

Other aircraft concepts were not studied.

4 Group Design Project of the MRT7-3R Meridian Flight-Refuelled Airliner (Ref. 7)

This design was performed before the study described in Para. 3, but shows, in considerable detail, design issues of flight-fuelling.

A family was designed to that development costs could be spread over a range or aircraft types and to investigate the possibility of civil flight refuelling such that an airliner sized for 3,500n. miles could efficiently fly at 7,000nm, following refuelling.

The family included:-

- The MRT7-8 which was a relatively conventional aircraft in the Boeing 787 class, which could carry 300 passengers, 7,000nm.
- The MRT7-3R utilised most of the airframe of the -8, but had a smaller wing and fuel capacity to give a range of 3,500nm between refuellings, afforded by a lower rear fuselage receptacle.
- MRT7-T uses the same basic airframe as the -8 but can be used as a civil tanker. This version has an actively-controlled,

retractable forward boom (Fig. 6.). Extensive design, modelling and safety analyses were completed and showed the viability of this concept.

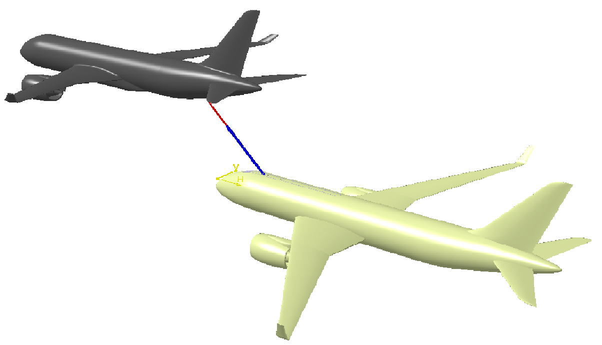

Fig. 6 MRT7 Family

A CAD model of the refuelling boom concept is shown in Fig. 7. The aircraft used the hybrid laminar flow, negatively scarfed engine intakes shown in Fig. 8. These should reduce fuel burn and intake noise. The aircraft utilises advanced avionic systems which include automatic refuelling-boom docking.

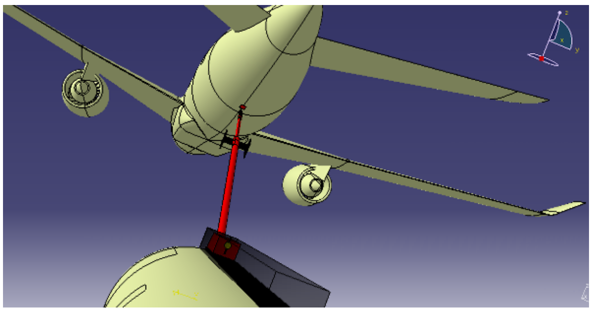

Fig. 7 Boom

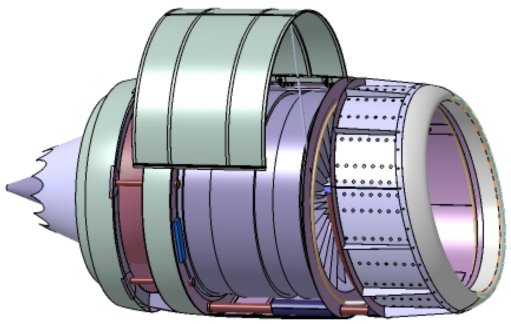

Fig. 8. The MRT7 nacelle with cowl doors open

The design study is now complete and initial conclusions indicated that the air-to-air refuelling of civil aircraft may have economic advantages on routes beyond 4,500nm, with fuel costs above $3US/G. This will require a global network of tanker fuelling hubs to be established and the psychological acceptance of fare-paying passengers that in-flight refuelling of civil aircraft is a safe procedure to follow.

5 Group Design Project of the A-6 Greenliner long-range Natural Laminar Flow Airliner (Ref. 8)

This project was also completed prior to the study described in Para. 3.

Four design variants were designed, the baseline version being the V-tailed composite structure aircraft (Fig. 9.).

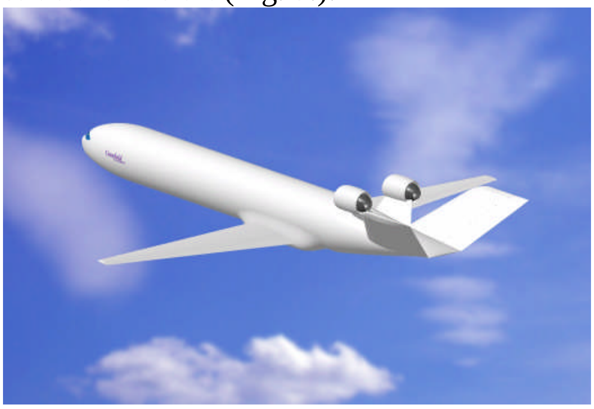

Fig. 9 A-6 Greenliner

The performance is that of a long-range, high-capacity aircraft in the class of the Boeing 777 or Airbus A330-600. Great efforts were made to reduce fuel burn and aircraft noise whilst producing low operating costs and high passenger comfort.

The wing was designed to use a Natural Laminar Flow (NLF) aerofoil section with a very high aspect ratio to achieve significant drag reductions and thus reduce the fuel consumption. This also achieved a large direct reduction of carbon emissions. This decision however, led to an unswept wing which limited the cruise Mach number to 0.74. The aircraft's engines were high-mounted on the aft fuselage with a 'vee' tail to provide noise shielding. All team members took care to achieve weight reductions through trade-off studies. Opportunities for better comfort and health of passengers during flight were also explored during the design of the A-6 cabin. These took the form of significantly increased fuselage cross-section, improved seating, combined with a higher humidity and lower cabin altitude fuselage (Fig. 10.).

Fig. 10 A-6 Internal

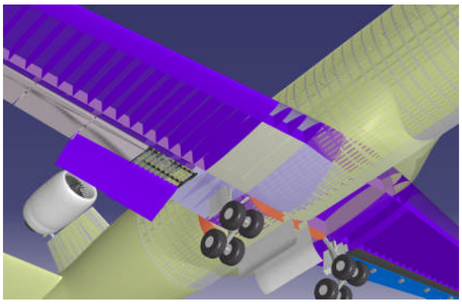

Fig. 11 A-6 Landing Gear

The pylon configuration would allow future use of large-diameter prop-fan engines.

Acquisition and operating cost estimates showed that the aircraft should be competitive with aircraft planned to be operated in the 2020 period, but the unswept wing required innovative design solutions to allow the main landing gear to be stowed (Fig. 11).

Fig. 12 A-9 Box wing aircraft

The main penalty of the aircraft was that it's cruise speed is only 90% of current aircraft values. This will lead to small increases in flight duration at short and medium ranges. The increased cabin volume and humidity, low cabin altitude and advanced avionics will make the aircraft more comfortable. This should give significant compensation for the increased journey times, as should lower fares than those for other aircraft that would follow with increased fuel costs and if carbon taxes were to be imposed.

6 Group Design Project of the A-9 Dragonfly mid-range Box Wing Airliner (Ref. 10)

The A-9 was designed to be a mid-range, mid-capacity aircraft, to act as a replacement for the Boeing 767/Airbus 330 class of aircraft. Fig. 12. shows the aircraft configuration.

The lifting surfaces, divided into four wings, required particular attention such as working out the load carried by the joint linking the two wing tips and the connection between the fins and the aft wing. Moreover, the unconventional configuration of the aircraft induced challenges regarding the task of each control surface. In addition, constraints about rotor and tyre burst were raised due to the engines and main landing gears locations which were satisfied by minor design changes.

The A-9 is a more-electric aircraft, integrating two CF-6 engines upgraded to become bleed-less power-plants; this solution lead to all the airframe systems being electrically powered, such as the ECS, the IPS and the actuation system. In addition, innovative features were integrated, such as proposing an alternative cockpit layout allowing a disabled pilot to fly the aircraft.

To minimise weight requirements, an Avionics Full Duplex Switched Ethernet (AFDX) network and distributed Integrated Modular Avionics (IMA) was incorporated. Standard modern processor units and accessories were all integrated in cabinets to form the system platform. This approach reduces the number of avionics hardware components through resource sharing and software implementation. The system was designed to be fully integrated and easily maintainable and upgradeable.

Due to the box wing configuration of the A-9, cargo loading was found to be a problem. Standard loaders could not be used as there was increased risk of hitting either of the wings. In order to get around this, a special feature was designed in. The cargo door would split in two and have a 6 degree sweep angle on it. This allowed the bottom half of the door to be used with a single container loader that would come in at an angle and meet the door (Fig. 13.).

Fig. 13 A-9 Cargo Loading

The unit acquisition cost is predicted at $128 million, yielding a break-even point estimated at 272 airframes. Low operating costs mitigate the A-9's turn-round challenges of high aft wing maintenance and airport interface issues pertaining to cargo loading.

7 Conclusions

Aircraft-related Global Warming is recognised as a serious issue which may increase in the future. It must be quickly mitigated by new operational, economic and technological means.

Conventional configuration aircraft, optimised for 4,000n miles, but using advanced engines, systems and materials, can offer some 20% improvements in fuel burn and 13% costs, relative to current aircraft.

Conventional-configuration, advanced systems technology-aircraft using civil air refuelling offer significant fuel improvements for 8,000nm flights. These are up to 40% savings relative to current aircraft, with some 20% D.O.C. improvements. Such operations, however, require the establishment of a global refuelling system, as described in the MRT-7 study.

Intermediate technology aircraft configurations, such as the Natural Laminar Flow Cranfield A6 Greenliner, should be able to significantly reduce costs, noise and Global Warming. This has modest risks but requires lower cruise speed. This is less convenient for passengers and increased crew costs on long flights, where extra flight crew are needed. The A-6 project examined many technical issues associated with this concept, without revealing insurmountable problems.

The box-wing concept is promising, in that an aircraft with reduced footprint can produce significant fuel & cost benefits at mid and long-range operations. The A-9 project confirmed fuel and cost savings of some 40% and 15% respectively relative to current mid-range aircraft, and 40% and 20% for long-range aircraft. There are considerable technical risks associated with this concept, as shown in the A-9 project. This concept would benefit from more research.

It can be seen that current configurations can significantly mitigate fuel burn and costs, if associated with advanced systems, engines and structures. These benefits can be further improved by the use of civil flight refuelling for longer ranges.

More novel configurations, such as natural laminar flow and box wings offer more advantages of similar orders of magnitude, but at more risk.

Studies should continue into broader aspects of global warming – not only fuel burn, and the noise prediction described here should be improved.

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