A GREEN ALTERNATIVE FOR PILOT TRAINING

D.P. Heatley*, R. Johnston*, R. Canders*, M. Mullan*, R. McRoberts*, M. Duffy*,
T. Eijgelshoven, F. Pronk**, K. Myerscough**, J. de Jong**, I. van Dartel**,**
M. van den Hoven**
***School of Mechanical and Aerospace Engineering, Queen's University Belfast.**
****Faculty of Aerospace Engineering, Delft University of Technology.**

Keywords: *Battery, general aviation, sustainable, electric*

Abstract

Growing concern about global warming and rising fuel prices are focusing attention on sustainable design. In light of this trend, an international design exercise was conducted with the aim of investigating the viability of a carbon neutral trainer aircraft. After careful evaluation of existing technologies and those nearing market entry, a proposal was made for a battery powered, 4-seat aircraft. The preliminary design focuses on the propulsion system, the construction materials and the complete life cycle of the aircraft.

1 Background

Recent years have seen a large increase in international attention on global warming. Governments worldwide are signing treaties with the aim of reducing carbon emissions, most notably the Kyoto Treaty. Recently the European Union opened talks with representatives of the General Aviation market about reducing emissions in their field of operation [1].

These are the main factors that led to the preliminary design treated in this paper. Keeping future generations in mind, the major focus was put on the sustainability of the design, but the fact that the solution would have to be economically viable meant that production and operating costs have been considered in detail as well.

2 Design requirements

The focus of the design was on sustainability, yet if a sustainable design is to be effective it will have to be competitive as well. Both price and performance of the aircraft have to be similar to existing aircraft.

The complete list of requirements applied for the design exercise was as follows:

- CO_2 neutral life cycle
- Production costs: $200,000
- 4 seat aircraft (including pilot)
- Number of flights: 12,000
- Flight hours: 20,000 hrs
- Life span: 30 years
- First flight: 2010
- Production volume: 5,000 units
- Range: 500 nm
- Cruise speed: 200 km/hr
- Take-off distance: 500 m
- Certified for PPL training

The CO_2 neutral life cycle is self-explanatory. Production costs, life span, cruise speed and take-off distance are all comparable to modern general aviation aircraft. The range requirement was reduced slightly to 500nm during the design process to keep the mass fraction of the batteries reasonable.

To keep a focus on sustainability beyond carbon emissions, production and end-of-life disposal methods were carefully examined as well. The aircraft was designed to exert a minimal energy footprint with little environmental impact.

3 Concept generation and selection

The two main categories considered during concept generation were construction materials and propulsion methods. The addition of the carbon neutral requirement resulted in unexpected directions after the qualitative trade-off study.

3.1 Materials

For materials only three candidates were seriously considered: wood, aluminum and composites.

Aluminum was heavily demerited by the energy intensive processes used in its synthesis, manufacture, and recycling. During recycling a lot less energy is put into the process than during initial synthesis, but unfortunately recycled aluminum cannot be used in production aircraft [2].

The negative carbon footprint of wood weighed heavily in its favor. In spite of wood's lower strength-to-weight ratio against man-made composites, its manufacture and machining have a relatively small energy footprint.

3.2 Propulsion

Four options were considered: batteries, fuel-cells, a hydrogen fueled gas turbine and a conventional diesel engine using bio-fuel.

Current bio-fuels are not 100% CO2 neutral [3], and the amount of agricultural area needed, coupled with the ecological and socio-economical repercussions involved, considerably detract from its advantages. Technological advances in biofuels promise to solve many of these issues, but others such as gelling at low temperatures [4] are not likely to have a solution by 2010.

Currently 75% of the Hydrogen production is obtained as a byproduct of the refraction of natural gas [5], but as dependence on fossil fuels decreases other ways of producing hydrogen will have to be used. The most likely candidate is electrolysis, which uses electric energy but is an inefficient process. In comparison with batteries, two extra energy conversions have to take place before hydrogen becomes usable. Hydrogen faces major difficulties with storage and a distribution infrastructure. By contrast, batteries are readily available and electricity networks are widespread.

3.3 Final concept

After performing a full qualitative trade off, the final proposed concept consists of a battery powered, propeller driven aircraft, mainly constructed from wood. As with most fully electric vehicles, range became the overriding issue. In order to meet the range requirement, low drag is essential. Modern day glider aircraft have excellent drag characteristics, hence the design is largely in the mold of a motor-glider.

4 Aerodynamics

Ensuring adequate performance for the aircraft requires the wing to reach as high as possible Lift-to-Drag ratio. Reaching this goal requires selecting an airfoil with low drag characteristics, and designing a wing planform with minimal induced drag.

4.1 Airfoil Selection

NACA 6-digit airfoils and the more recent NASA Natural Laminar Flow (NLF) sections show relatively low drag when compared to widely used turbulent airfoils. However, it appears to be difficult to combine a large laminar bucket with low drag in the laminar region with the NACA and NLF airfoils. After a consultation with L.M.M. Boermans (a lecturer in aerodynamics at the TU Delft), the decision was made to use a laminar airfoil developed by the University of Stuttgart, the AH 93-K-131/15. It is a 13% thick airfoil, with maximal t/c at 50% chord, and a design lift coefficient of 0.2 at Re = 2.5e6.

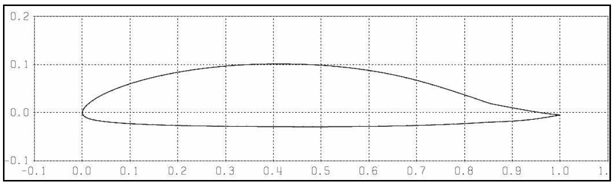

Fig. 4.1. AH 93-K-131/15 Airfoil

This airfoil exhibits a large laminar bucket combined with a low drag count. Compared to NACA 6-digit and NLF airfoils at similar Reynolds number, the AH airfoil shows at least 1 drag count less at the same Cl, combined with a more extensive laminar bucket. This airfoil reaches its maximum lift coefficient in fully turbulent flow ensuring the aircraft will not stall catastrophically if the wing surface happens to become contaminated by rain or bugs. This, combined with very gradual stall characteristics, made it a good airfoil choice for a trainer aircraft.

The original airfoil camber is tailored using XFoil to reach a cruise lift coefficient of 0.38 while remaining at the lowest drag point.

4.2 Wing Planform Design

The least induced drag is achieved with an elliptical lift distribution. Maximizing performance while keeping manufacturing complexity low rules out the use of an elliptically-shaped wing, as well as the use of a twisted planform. An untwisted, triple-tapered wing is chosen. It was mathematically estimated by L.M.M. Boermans that the geometry chosen displays only a 0.9% drag increase compared to a perfectly elliptical lift distribution. The final wing dimensions are as given in 4.2:

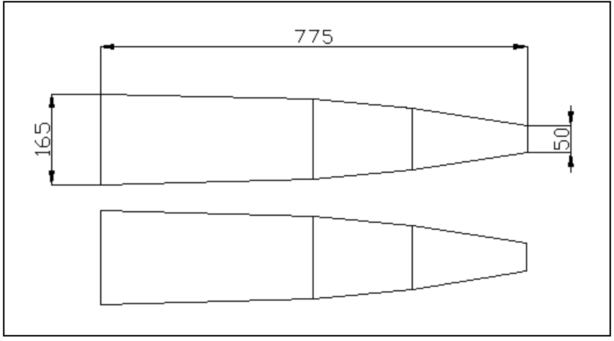

Fig. 4.2. Wing Planform (dimensions in cm)

4.3 Lift and Drag Estimations

The lift distribution is estimated using Diederich's method, producing Fig. 4.3.

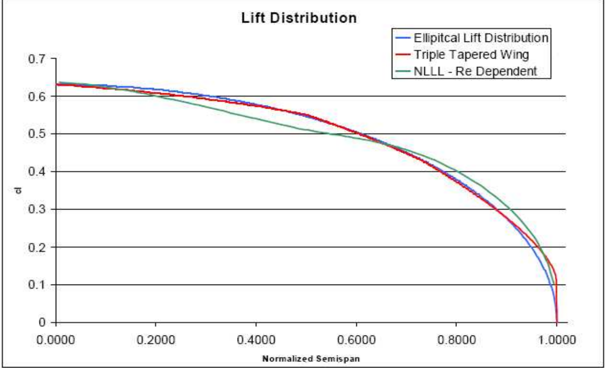

Fig. 4.3. Spanwise Lift Distribution

From Diederich's method the spanwise airfoil contribution is computed, and from there, using Xfoil, the required angle of attack. The required cruise lift coefficient is reached at around alpha = 1.5 to 2° using 2D airfoil data, so approximately around 3° angle of attack for the total wing.

Wing drag is estimated using strip theory also used to predict the maximum lift coefficient. For cruise, the conditions at the root, tip, and every taper change are estimated, and linearly extrapolated for the rest of the wing. This yields a CD_{CRUISE} of 0.0077

A total estimate is required for the lift independent drag of the airframe with and without the landing gear retracted, minus the wing contribution. Each section of the aircraft will be calculated separately, then summed and multiplied by a type factor of 1.3 taken from Howe [6] to account for interference and pressure drag. Excrescence and trim drag are taken from statistical data for similar aircraft. Each part of the fuselage is treated as being in full turbulent flow due to the propeller slipstream. A wetted area is calculated and a reference length is chosen to provide a Reynolds number. Only cruise Reynolds numbers are considered here. Using the turbulent skin friction formula

$$CF = 0.455(Re)-2.58$$

a skin friction coefficient is calculated. This is multiplied by S_{WET}/S to supply that part's drag coefficient relative to the wing area. The results are displayed in Fig. 4.4.

dCD Fuselage	0.001383
dCD Fin	0.000415
dCD Tailplane	0.00047
dCD Boom	0.0005
dCD Excrescence	0.0002
dCD Trim	0.000277
Form Factor (Howe)	1.3
CD0 minus Wing	**0.00422**

Fig. 4.4. Lift Independent Drag Summation

4.4 Summary of Results

The aerodynamic characteristics of the aircraft are summarized in Fig. 4.5.

A	12
s	$20m^2$
b	15.5m
C_{ROOT}	1.68m
C_{TIP}	0.5m
$C_{L\text{-}CRUISE}$	0.387
$C_{LW\text{-}TO}$	1.23
C_{LMAX}	1.51
$C_{LW\text{-}\alpha}$	$0.083deg^{-1}$
$C_{DW\text{-}CRUISE}$	0.0077
$C_{DW\text{-}TO}$	0.0605
$C_{DW\text{-}STALL}$	0.138
$C_{DCRUISE\text{-}TOTAL}$	0.0116
$C_{MW\text{-}CRUISE}$	-1.025e-2
$C_{MW\text{-}STALL}$	-7.27e-2

Fig. 4.5. Summary Of Aerodynamic Characteristics

Estimations omitted in the aerodynamic considerations are the complex wing-fuselage interactions, the complex propeller slipstream effects, the effect of negative lift from the tail plane and its induced drag, and the vortex effects at 90% span due to flap deflection. Much more in-depth design will be needed to properly assess all these effects. The shape of the fuselage will have to be optimized to minimize flow separation and interference drag. Another drag source omitted in the previous analysis is the possible effect of the split joint at 72% span, where the wing can be detached for the loading of the batteries. A truly accurate and complete preliminary drag estimate is well beyond the scope of this design exercise. Indeed, it requires a thorough analysis of complex aerodynamic effects which would call for more resources and knowledge than available for this project.

5 Structural Design

5.1 Spar Sizing and Rib Placement

Two spars are employed either of which alone can sustain flight loads, giving the aircraft an infinite lifespan. The spars are designed using a shear force and bending moment analysis. Ribs are used to prevent excessive warping of the skin and to reinforce the wing at changes in taper.

5.2 Battery Placement and Motor Mount

Two thirds of the batteries are placed in the wing, and alleviate the bending moment induced by flight loads much as liquid does in the wings of a fossil fuel powered aircraft. The battery packs are cylindrical in form and are slid into the wing from the wingtip via a guide rail. The outer casing of the battery is sufficiently pliable to bend in sympathy with the structure around it but does not permanently deform. Fig. 5.1 below illustrates the method used to insert batteries into the wing: the wingtip section from the last taper outwards is removable. This method is common among glider designs where ease of storage is a key factor.

While the removable wing tip design does cut the wing torsion box, placing a rib at the edges of the cut significantly reduces negative effects.

5.3 Undercarriage Attachment and Centre Wing -Box

The centre wing box passes through the fuselage under the rear row of seats, giving favorable stability margins. The landing gear is placed just forward of the wing box, requiring only a small further section of the fuselage to be strengthened. Diagonal struts bracing the gear in down position are attached to strengthened points on the fuselage structure.

5.4 Tail Construction

The tail boom consists of a number of beams connected by wooden hoops giving the fuselage support and shape. The skin is load bearing. With a third of the total payload of batteries stored in the tail, careful consideration is given to the empennage-fuselage joint. At the base of the rudder a hatch gives access to the battery storage compartments, similar in design to those in the wing.

5.5 Landing Gear

The retractable landing gear folds up into wells underneath and to either side of the cabin. The drag penalty induced from fixed gear is too great to allow its use, in spite of the increased cost and mechanical complexity of retractable gear. The tail wheel is a standard simple fixed design, raised to give appropriate visibility while taxiing.

6 Propulsion

Since the introduction of mobile electronic devices battery technology has undergone massive improvement [7]. It is only recently that batteries have become powerful enough for aviation usage, and there are technological barriers to overcome in their application on this scale.

6.1 Batteries

The major problem with the use of current battery technology is the mass of the battery packs. In recent years several companies and research institutes have begun development of high capacity batteries, mostly with the aim of applying them in electric vehicles. A number of solutions exist, but the most notable one being the new Li-S technology [8]. This technology is expected to achieve 450 Wh/kg by 2010 which makes it a workable solution. The technology has furthermore been applied in QinetiQ's Zephyr [9] and thus is a flight-proven design.

The lifetime of a rechargable battery is defined to be the number of recharge cycles it can undergo until the fully charged battery only has a capacity of 80% of the initial capacity of the battery. Li-S batteries currently have a cyclelife of around 300 full depth-of-discharge cycles, but the cyclelife is expected to be around 500 cycles by 2010 [10]. Even though this is still rather low compared to Li-ion batteries (which can reach up to 3000 cycles it will be shown in section 8 that this is a workable lifetime.

Recharge time is another issue facing battery-powered electric vehicles which can be solved by making the batteries exchangeable. This way flight operations will only have to be interrupted during the brief period in which the depleted batteries are taken out and (fully) charged ones are put in.

6.2 Electric motor

Electric motors have been around for decades and have many advantages compared to combustion engines.

One of the best characteristics of electric motors is their high efficiency. Current motor efficiencies of 90% are common, with newer motors reaching up to 98%. This makes the use of these motors in transport vehicles highly attractive.

Furthermore, the very limited amount of rotating parts increase reliability compared to reciprocating engines, while decreasing the required amount of maintenance. Both these effects will be appreciated by general aviation operators.

Another positive effect is the independence of the motor on oxygen, removing the need for mixture controls.

Compared to noisy combustion engines, the relatively silent hum of an electric motor could benefit both people on the ground as well as cabin comfort.

6.3 Final remarks on battery system

As electricity and water don't match very well, care has to be taken in the design phase to make sure the electric system is properly protected from the elements. At the same time users should be properly protected from being exposed to the high voltages used.

A positive effect of using a battery system is that battery technology is expected to advance as time passes. The result being that with a minor redesign of the battery packs, the aircraft performance (mainly its range) will improve, while operating costs might go down even further.

7 Production and Assembly

7.1 Material Choice

Material selections are summarized in Fig 7.1.

Wing	
Skin	Birch Plywood
Spar	Laminate Douglas Fir
Ribs	Birch Plywood
Ailerons	Laminate Sitka Spruce
Fuselage	

Bulkheads	Laminate Douglas Fir
Longerons	Laminate Douglas Fir
Skin	Birch Plywood
Ribs	Birch Plywood
Struts	Laminate Douglas Fir
Empennage	
Stabilisers	Laminate Sitka Spruce
Elevator/rudder	Birch Plywood
Landing Gear	
Struts	Mild Steel (AM350)
Main Tire	Goodyear Flight Special II
Tail Tire	Matco T-5

Fig. 7.1. Material Selection

Due to the difficulty in obtaining Sitka Spruce in bulk at the quality required, laminated Douglas Fir has been selected as the main structural material which carries flight bending loads and landing impact forces. While Douglas Fir is slightly heavier than Sitka Spruce, it has greater structural strength. The use of laminated sections as opposed to large solid planks reduces supply chain difficulty as smaller pieces of wood are required. Douglas Fir is generally not as straight grained or defect free as Sitka and thus has not generally been used in aircraft on the scale proposed here.

7.2 Manufacturing Processes

Traditionally light aircraft are hand crafted in a manual-labour intensive process, with large amounts of waste and cumbersome quality control procedures. In line with the carbon-neutral requirement manufacturing and assembly is highly automated, reducing scrap and increasing overall product quality.

Joints between members are both fastened and bonded. Brass screws and epoxy resins are used to affix the outer skin to the structure. For load bearing joints bolts inserted parallel to grain run are employed with smooth bored holes. As the load bearing capability of a bolt depends greatly upon the surface finish of the hole, automated drilling processes are employed to ensure repeatability. Similarly the load bearing capacity of a resin bonded joint depends upon the evenness of adhesive application, which is also automated. The overall structure is self-reinforcing with ribs and other smaller internal structural components acting as side plates to the spar, undercarriage attachment points, and other critical locations.

The exterior surface coating of melamine-based resin acts as both a fire-retardant and a protective coating against UV and weather. It can take a scratch resistant aerodynamically smooth surface finish capable of attaining the low drag estimated in section 4. Melamine is widely used in industry today and lends itself to automated coating processes. Between the birch plywood skin and resin surface coating is an anti-lightning foil that acts as a sacrificial layer. Inexpensive wet layup is employed for the control surface skins with room temperature cure resins and natural fibre ply such as flax. Surface finish is not critical as the flow is fully turbulent over the control surfaces. The composite is lighter and cheaper than a wooden counterpart.

7.3 Maintenance and Disposal

Wood does not have a fatigue life and if properly preserved will carry load indefinitely. Inspection panels are built into the frame to provide easy access for inspection and routine maintenance. Damage to the frame's protective coating, allowing corrosion or moisture ingress, is the greatest danger and is combated by regular inspection. Application of a surface patch is inexpensive and simple.

It is the responsibility of manufacturers to provide products that are environmentally responsible throughout their entire lifecycle, including disposal. Wooden components can be recycled or rendered down for pulp and metals used are fully recyclable, leaving a very small amount to go to landfill.

8 Costs and operations

As mentioned in section 2 a sustainable design can only be effective if it is financially viable and practical to operate.

8.1 Costs

The intitial cost estimate is based on cost comparisons, historical trends and methods described in Roskam [11]. A rough estimate indicates that the concept can be build for \$170.000,-, being 40% motor and batteries, 35% aircraft systems (incl. Instruments), 8% material costs, 4% labour and the remaining 13% are spent on various items such as landing gear, tooling, quality control and other unforeseen costs. Adding a reasonable profit margin still keeps the concept cost competitive.

The most interesting part however, are the operating costs. At an estimated cost of \$50,000 per battery pack [12], the 'fuel' costs are substantially lower than current AVGAS costs. If the batteries show no improvement over the next few years, 300 cycles with 4.8 flight hours per cycle, make a total of 1440 flight hours. If electricity costs are set at \$0.13 per kWh and a single charge needs 140 Kwh, the total fuel costs per hour become

$$\frac{140 \cdot 0.13}{4.823} + \frac{50000}{1447} = 38.32 \text{ \$/hour}$$

A Cessna 172 uses approximately 6 gallons of AVGAS per flying hour [13], at current AVGAS prices in the US of \$5.50 per gallon [14], total fuel costs per hour for a Cessna are \$33,-. In Europe however, the price of AVGAS is more towards \$10,- per gallon, doubling the costs and making battery powered flight very interesting.

Maintenance costs will also be lower due to the mentioned low maintenance requirements of electric motors. Together with the reduced fuel price, electric aviation is likely to become a good competitor.

8.2 Operating an electric aircraft

Operating a battery powered aircraft is very similar to any conventionally fueled aircraft. Minor differences are the fact that the aircraft mass remains constant during the flight, which results in handling characteristics remaining the same as well. Also, the simplicity of operating an electric motor (ie. no mixture controls), should help simplify the flying experience.

Refuelling the aircraft will be as simple as either charging the batteries using the charging station or replacing the batteries if time is of the essence. The latter task should not take much longer than filling gastanks with AVGAS.

As the electric motor requires less maintenance, time between maintenance could well be increased, resulting in an aircraft which has a higher productivity.

9 Conclusions and Recommendations

9.1 Conclusions

The concept study performed has shown that, with increasing focus on sustainability and rising fuel prices, an electric aircraft not only is an attractive alternative, but also has desirable characteristics, such as low motor maintenance requirements and low operating costs.

As with all full electric vehicles the storage of electric energy in batteries is still the limiting factor. Developments on the battery front have seen interesting improvements however, which may result in fully electric and highly competitive aircraft in the near future.

9.2 Recommendations

If electric or sustainable aircraft are to become successful sooner rather than later, several aspects need to be considered.

First of all battery development needs to be monitored and if possible stimulated. Also, if the focus is on sustainability, recycling methods for the batteries used need to be investigated and improved.

Secondly general aviation aircraft should be made to resemble their high performance sailplane siblings. This will help increase the range of battery powered aircraft, or in the worst case decrease the fuel consumption of coventionally fueled aircraft.

Last but not least, legislators should start considering certification of alternatively powered aircraft to speed up the certification process. This will reduce development time and thereby decrease investment risk.

If all these recommendations are executed, the future for electric aviation looks bright.

References

[1] Aviation International News http://www.ainonline.com/news/single-news-page/article/egama-lobbies-for-general-aviation/.

[2] Das S, Kaufman J, *Recycling Aluminum Aerospace Alloys*, Metals Minerals and Materials Society, 2007.

[3] Heinen R. *Carbon Footprint Of Biofuels And Petrofuels*. SRI Consulting, 2007.

[4] Shumaker G et al. *A Study On The Feasibility Of Biodiesel Production In Georgia*. Georgia Department of Agriculture, 2003.

[5] Paster M et al. *Annual Progress Report On Hydrogen Production*. US Department Of Energy, 2007.

[6] Howe D. *Aircraft Conceptual Design Synthesis*. WileyBlackwell, 2000.

[7] M-Power, http://www.mpoweruk.com/

[8] Sion Power, http://www.sionpower.com.

[9] Qinetiq press release. http://www.qinetiq.com/home/newsroom/news_releases_homepage/2007/3rd_quarter/qinetiq_s_zephyr_uav.html.

[10] Personal communications with Dr. Neil White, Sion Power UK.

[11] Roskam J, *Airplane Design*, DAR Corporation, 1989.

[12] Personal communications with Dr. Neil White (Sion Power UK) and Crijn Bouman (Epyon B.V.).

[13] PlaneQuest, http://www.planequest.com/operationcosts/op_cost_info.asp?id=98.

[14] Aviation Fuel Pricing, www.100ll.com.

Copyright Statement