BLENDED WING BODY AND ALL-WING AIRLINERS

Egbert Torenbeek

Introduction

Famous and scientists and engineers such as Lord Kelvin, Lanchester, Von Kármán and others have made futuristic predictions about aviation and proved to be amazingly wrong. I do not intend to make prophecies about the 21st century of aviation. Rather I will try to expose and appreciate some properties of one innovative civil aircraft concept that is considered by many aviation experts as a promising alternative to the presently existing airliner configurations.

In the past proponents of unconventional concepts have claimed considerable or even revolutionary performance gains, but predictions were often based on first principles. Nevertheless some of them were apparently so convincing that fundings for in-depth research and applied design studies could be raised. But recent advances in computational capabilities in major aeronautical disciplines, combined with advancing MDO techniques enable investigators to go into considerable detail leading to a large technology base which was, however, not always made accessible to the aeronautical community.

One of the most promising concepts, the blended wing body (BWB), has been around for quite some time and many of you will have an idea of what has been claimed as its promises. It can be considered as a major step towards the realisation of a pure flying wing (or all-wing aircraft), which has been advocated already before and during WW2 by several designers with high reputation as the ultimate ideal for the aircraft architecture. The BWB has not completely eliminated the fuselage body and the major objective of this lecture is to explain why it makes sense to stop halfway the evolution from a conventional architecture to the most radical shape.

The dominant configuration

When we look back one century of aviation we notice that the general arrangement of the first practical aircraft, the Wright Type A, would be considered as pretty unconventional if it were used for a present-day airliner. In fact, the Piaggio Avanti, with its tail-first and twin pusher propeller arrangement, shows some similarity but it is unlikely that Piaggio designers consider their aircraft as an imitation of the Wright Flyer.

It has often been said that technological progress has never been as fast as during the recent decennia. But would you think that this applies to aviation when you realize that the Boeing 707 -- the first jet airliner with transatlantic capability, cruising at a speed only 20% below the speed of sound -- flew only half a century after the primitive Wright aircraft? And would you still insist that we live in a technological revolution when you look at another 50 years later (the present year 2007) when the Boeing 787 is planned to roll out. Superficially one might observe that since the B 707 merely the number of engines has been halved and the size increaesed. So, what’s new?

A more realistic observation is probably that the most significant mutations in the aeronautical evolution have occurred between 1940 and 1960, two decennia of immense technical progress, followed by a period of consolidation and gradual improvements, resulting in the presently dominant airliner configuration. This established architecture has formed the solid basis for another revolution: *the almost explosive expansion of civil aviation into an unrivalled efficient, economical, safe, reliable, and environmentally friendly transportation system.* In particular the appearance in 1968 of the Boeing 747 wide body jet with its large and efficient high bypass engines contributed to the popularity of flying. For the airlines the 747-400 became the economic workhorse over transatlantic and much longer distances.

During the past four decennia many new types for long, medium and short ranges emerged and have been further improved in many areas of technology and commercial transportation. The Airbus A380 will offer the ultimate in terms of passenger comfort and airline economy over long ranges. But will it be the first of a new, or the last of an old generation? In other words: is there a better alternative for the presently dominant configuration, for example in the form of the BWB or another innovative concept?

Energy efficiency

The efficiency of fuel energy conversion is a comprehensive figure of merit for any airliner and one of the best criteria to compare a new configuration such as a BWB with the dominant configuration. It is expressed in terms of passenger seat-miles produced per liter fuel, which is important from the point of view of both transporation economy and atmospheric pollution. The present expression shows the various factors involved in this quantity, which is not a constant during the flight, but we will consider a mean value. These are:

1. The ratio L/D in horizontal cruising flight is the most significant aerodynamic performance parameter for long range airliners.
2. The overall (propulsive) efficiency η denotes the fraction of the fuel heat content that is converted into useful thrust energy to balance the drag. A feature of jet propulsion is that this efficiency increases with airspeed.
3. The specific heat content of gas turbine kerosine type fuel invariably amounts to about 33mJ per liter. For liquid hydrogen it is four times less, in spite of its high energy content per unit mass. Possible LH aircraft being studied at present will therefore be very voluminous and rather more costly to operate. Probably hydrogen fuelled aircraft will be used not until fossile fuels will become unaffordable.
4. The aircraft AUW per seat, W/N, is determined by a large number of factors associated with the type of airplane, structural material and efficiency, etcetera. Technological improvements mostly act in favour of reducing W/N, but at the same time this has been counteracted by safety and operators requirements becoming constantly more stringent. Aircraft weight varies typically between 5 kN and 8 kN per seat, for short-range and very long-range aircraft, respectively. The higher value reflects the penalty that has to be paid for carrying a large amount of fuel onboard during the first flight sector.

Since 1960 there have been numerous technological improvements in all areas, but the greatest progress came from gas turbine engine developments, in particular high bypass turbofans. Modern engines achieve 35% to 40% installed efficiency at cruising speed. Although this figure can still be improved, we should realise that it is almost twice as high compared to 50 years ago – an average improvement of 1.5% per year. Overall, since the Comet the seat-km production per liter fuel has increased (by a factor of almost four) to about 40 to 50, and is now comparable to a typical mid-class automobile.

Main configuration choices

Presently developed designs such as the Boeing 787 and Airbus 350 continue to have a traditional general arrangement, which has probably been adopted for very pragmatic reasons. Or have decision makers listened to the following oneliner used by astronomers: *"Never run behind a bus, a woman or a new cosmological theory, because there will be another one within a few minutes"?* This could be a bad advice when running behind the lady of your dreams or the last bus of the day. An example of the first kind could be the BWB, the second case could be that the predictable shortage of fossile fuel will force the aeronautical community to switch timely to hydrogen propulsion, even though it is economically unattractive.

In the process of aircraft development it is necessary to make an assessment of what an innovative configuration will offer in an *industrial environment.* This means that a set of design requirements must be satisfied and answers will have to be given to the question in what respect the new configuration will be helpful to improve economics, environment and safety, and what are the risks that it may eventually not satisfy expectations. The road to better, cheaper and quicker aircraft development now comes to a crossing point. Instead of continuing just to improve the standard configuration, more innovative and radical general architectures must be looked at seriously.

Configuration matrix

In looking at possible alternatives it is helpful to look at the present diagram depicting a matrix of configurations collected by Deutsche Airbus. Some of them have been studied during the past decennia and have been nicknamed.

1. Horizontally are shown the various combinations of one, two or three lifting surfaces to provide lift and longitudinal trim. The concept with joint wing tips has an unusual appearance, although it has some resemblance with the old biplane, adapted to high speeds.
2. Vertically are shown four alternatives to allocate the passenger cabin: inside one fuselage, inside two fuselages, partly inside fuselage and wing, and completely inside the wing.

In theory any deviation from the dominant configuration increases the number of permutations considerably. But the designer’s freedom has practical limitations, reflected by many open positions. For example: “the outside has to be bigger than the inside” and thus only large aircraft can contain human payload inside a wing with acceptable comfort and possibilities to escape in case of emergency.

The development and comparison of any of these new configurations is an enormous task and extremely challenging to the design community. It requires experienced, multidisciplinary design teams, availing of extensive and expensive possibilities to simulate complete aircraft on computer systems, often augmented by experimental facilities such as a transonic wind tunnel or remotely controlled flying models. Although today we focus on aerodynamic performance it should be noted that these unconventional concepts will have a major impact on items like structural loads, stiffness distribution and aero-elastics. In many cases the overall effect is not an improvement over the classical configuration. I will now briefly discuss a few of the most promising concepts.

Twin fuselage configuration

My personal favourite is the twin-fuselage configuration. Its main virtue is that the useful load is distributed laterally and axially in such a way that wing and fuselage bending moments are reduced considerably compared to the classical lay-out. For the same wing span and all-up weight the maximum wing bending moment is reduced by more than 50%, while the complete central wing section is very lightly loaded. This will reduce the wing structural weight considerably, or alternative a larger wing span can be selected. Up to now twin fuselage designs have received little attention from airplane manufacturers for reasons that nobody can explain to me.
The depicted medium range twin fuselage airliner was conceived by the Dutch consulting company ADSE, together with your present lecturer in the framework of a workshop with Airbus. It carries a passenger load of 250-300 in two single aisle fuselages. Relative to a classical single wide-body configuration the span has been increased by some 20% without excessive wing weight, and the total wetted area is slightly smaller. There are more of these effects, since the square cube law works in favour of this configuration. The two fuselages provide effective shielding of engine noise. This concept does not require major advances in design technology and alleviates or completely avoids most of the potential showstoppers for more radical concepts.

Lift/drag

The basic factors affecting the L/D ratio are based on the usual parabolic drag polar assumption.

1. Using a large wing span is a powerful means to improve the aerodynamic efficiency by reducing induced drag. Since this leads to a proportional increase of the structural wing weight, the choice of wing span is subject to optimisation. Configurations leading to reduced wing weight wil allow bigger spans, and thus higher L/D.
2. Reduction of the fuselage exposed area is limited by the need for providing sufficient space-related passenger comfort. The wing must be big enough to contain the required fuel or not to exceed a certain approach speed. Reducing tailplane size or even leaving them completely out is possible only with radically new concepts. Engine nacelles tend to be bigger with increased bypass ratio, the major parameter for powerplant efficiency improvement.
3. The Oswald factor has the reference value of 1.0 for a flat lifting surface with elliptical spanwise lift distribution, but is somewhat lower in practice. Certain unconventional wing shapes promise to exceed this value.
4. Finally, the profile drag coefficient based on wetted area expresses mainly surface friction drag due to the boundary layer. It may be reduced by obtaining

a larger percentage of external surface with laminar flow, instead of accepting the presently predominantly turbulent flow. One complicated way of achieving this is active laminar flow control (ALFC). Configurations allowing ALFC may have a better chance to survive the selection process of possible configurations.

The Wright Flyer achieved L/D=6, the DC-3 had L/D=14, and the B707 had L/D=18. It is remarkable that between 1950 and 1990 this figure has increased to about 20 for the B777 and A340, an improvement of only 10%, or 0.25% per year. Since over the same period the ratio span/(wetted area)$^{1/2}$ hardly changed from a typical average value 1.2, the L/D improvement is probably mainly thanks to smoother skin surfaces, a Reynolds number effect - airliners have become much bigger - and application of winglets. Apparently the dominant configuration is more or less doomed to a geometry that will not allow a significant improvement in the L/D ratio. Alternative configurations must be tried if we refuse to wait another half a century for an improvement in L/D of, say, 20%.

Oswald factor

Prof. Kroo at Stanford University made a study of the vortex-induced drag of non-planar wings, all fitting in front view inside a box of given span and height. In view of Munk's stagger theorem this also allows a staggered biplane and a diamond shaped set of joined wings. The induced drag is inversely proportional to the Oswald factor. Ludwig Prandtl has already derived around 1920 that the box wing has the lowest induced drag, but its vertical endplates are not lifting and increase profile drag and weight. The highest Oswald factor are obtained for the C-wing and for the box wing. Both may become attractive in the case of a wing span constraint, such as the well known 80 meter limitation.

Boeing C-wing

The principles of this concept are patented by I. Kroo and J. McMasters of Boeing. It carries the payload partly inside the wing and partly in the fuselage. The central wing uses thick, supercritical Griffith sections. The designers claim to have obtained a span loading effect without the disadvantages of very large all-wing aircraft by avoiding two passenger decks above each other. A span limitation to improve airport handling has been realised without the structural complication of folding outer wings. This concept is no longer under development, but it may be considered for application in more conventional designs as well, provided its aero-elastic problems can be solved.

Lockheed box wing

This design by Lockheed is intermediate between a joined wing and a pure box wing, originally analysed by professor Ludwig Prandtl. The upper and lower wings both carry about half of the lift and both have multifunction flaps/elevators/ailerons. A horizontal tail is not required. Wings are of very high aspect ratio, enabled by a favourable structural configuration. For long range airliners the provision of sufficient tank volume tends to be problematic and the undercarriage fairings will cause extra drag.

Northrop flying wing

The flying wing is the most radical way of reducing wetted area since it has only a very rudimentary the vertical tail, if any, and the horizontal stabilizer is completely absent. Moreover by distributing the useful load laterally along the wing its bending moment is reduced. Hence, wing span can be increased without making the structure too heavy. The flying wing has been advocated since the thirties by John Northrop and the B-49 was built shortly after WW2. It suffered from stability problems and lost the competition with Boeing's B-47, but forty years later Northrop was put in the right when the B-2 stealth bomber was developed.

All-wing airliner

The flying wing is not obtained from the classical design by just deleting the fuselage and the empennage. A fair comparison can be made only when the two concepts are designed to carry (roughly) the same useful load, still maintaining acceptable stability and control properties. The present flying wing airliner layout is based on the following assumptions.

- The inboard wing houses the passengers on a single deck, with baggage under the floor. It has the same gross volume as the conventional fuselage.
- The outboard flying wing has the same volume as the conventional gross wing.
- The total gross planform area is almost twice the conventional wing area, the lift coefficient correspondingly smaller.
- The wing is everywhere 1% chord thicker than conventional.
- The 96m span is 20% larger than the conventional span, nevertheless the aspect ratio is less than 6.
- Leading edge flaps are probably required since trailing edge flaps cannot be used. This will require a high angle of attack for take-off and landing.
- Two vertical winglets and ailerons with split controls provide directional stability and control.
- For the same take-off weight only three engines are necessary.
- Total wetted area is 7.5% less than the conventional aircraft.
- Based on the same friction coefficient and Oswald factor, L/D-max is 25% higher, primarily due to the big span.

For application as a civil transport aircraft the pure flying wing configuration is not necessarily appropriate. One reason for this is that a rather thin transonic wing does not have offer the large internal volume required to contain the passenger cabin unless at has a very large exposed area. In view of the much smaller fuselage wetted area compared to a wing with the same volume, it is not immediately obvious that all wing aircraft represent the best answer for a volume constrained aircraft. So it is worthwhile to answer the following fundamental question, which has been addressed only superficially in the literature on configuration design. *Suppose that a total volume (of useful load) to be transported is given, and that this volume can be distributed arbitrarily over the fuselage and the wing, is there an optimum allotment?*

An answer to this question will be obtained by means of a parametric study of the aerodynamic performance of wing/body combinations, varying between the conventional discrete combination to the flying wing.

Progression from conventional to all-wing

Combinations of wings and bodies which have been sized up and down and combined, so that they have the same volume available for useful load. Several basic assumptions were made to derive analytical expressions for the glide ratio or L/D.

For a typical cruise condition (M=0.8 @ 35,000 ft) the L/D of a pure flying wing appears to be rather disappointing. In this particular case it is better to have 40% of the volume inside the wing and 60% inside the fuselage. For a present day jumbo jet these numbers are approximately 20% and 80%. The results indicate that the flying wing had a far too low wing loading for this specified flight condition and could not fly close to its optimum lift coefficient. It would be helpful if a (much) higher cruise altitude or a lower Mach number could be selected, but this is not usually an option, firstly because the required engine size would increase considerably, as demonstrated by the slide, and secondly a low cruise speed is not attractive to operators. Repeating the calculation for different aspect ratios indicates that for all wing a/c there is very little to gain, while for conventional wing/body combinations high aspect ratios are favourable. These results are indicative that the pure flying wing might not be an attractive concept for transonic airliners.

The blended wing body (BWB)

These observations does not necessarily apply to the blended wing body (BWB), which is considered as a very low aspect ratio and thick inner wing combined with conventional high aspect ratio and thin outer wings. American, Russian and European teams claim substantial gains in take-off weight and fuel weight are claimed for the BWB compared to a conventional design. For example, for an 800 – 1000 passengers airliner with a wing span of 100 m, a cruise L/D=24.5 at M=0.85 could be achievable. This would mean a dramatic improvement in fuel efficiency.

Transformation of a ball into an airliner

Let us first assume that a classical airliner has to be designed for 800 passengers. The smallest surface area (660 m^2) is obtained when they are enclosed by a sphere with a volume of about 1,600 m^3. But the sphere has a huge pressure drag and the more usual cylindrical cabin is preferred, which has a three times bigger wetted area. This picture shows how -- at least on the backside of an envelope -- the dominant configuration can be completed with a wing, empennage and engines. The total wetted area amounts to 4,250 m^2 , cruise L/D=19.

We now consider the creation of a BWB. The same payload volume is transformed into a lifting disk with a thick supercritical section shape. Due to the twin deck passenger cabin the wetted area is slightly less than in the case of the tubular fuselage. Smaller wings than in the previous case can be added, but the span is increased. Relatively small verticals stabilise and control the aircraft directionally, the horizontal tail has been omitted, and the semi-submerged installation of just three engines causes little extra wetted area. The total wetted area amounts to 3,000 m^2, a reduction of 30%. The designers claim a cruise L/D ratio of 23, an improvement of more than 20%.

Boeing BWB

A large blended wing body for about 750 passengers on two decks has been created by McDonnell Douglas staff before their merging with the Boeing company. Substantial gains are claimed in take-off weight (-15%) and fuel weight (-38%) compared to a conventional design, while only three instead of four engines are required. These impressive figures are possible without new technologies; the credo is*: The configuration is the new technology.* Boeing has more recently developed a BWB for about 450 passengers on a single deck and has claimed that the BWB can be realized in the next decennium. Boeing has also studied designs with increased cruise Mach number up to 0.93, making use of technology developments from the Sonic Cruiser program. It is noticeable that the engines have returned in pods.

BWB design challenges

The design process of a BWB is far more complicated than usual. Moreover, major technical and operational problems have to be solved before the BWB can be considered as a viable airliner concept, as illustrated by this slide. The BWB is also subject to studies by Airbus and its European partners. A study team of the Russian institute TsAGI has studied similar configurations since the end of the eighties and found that some of theire problems are relieved or even disappear for the less radical hybrid configuration, which features a passenger cabin in the wing and inside a relatively small fuselage. Their 800 passengers design featured a wing span of 100 m, leading to a cruise L/D=24.5 at M=0.85. The associated airport handling problems have to be avoided by the use of folding outer wings. A similar costly option has been offered on the Boeing 777, but no airline has ordered it.

In order to compare the BWB with the traditional configuration a sketchy design has been made with the same useful volume and designed for the same cruise condition as the previous designs. The span was assumed equal to the conventional wing span. It was found that its planform and wetted areas were substantially lower and L/D-max some 25% higher, provided trim drag can be neglected. There are no trailing edge flaps, but slats are required on the outboard wing. This will result in a high stalling angle of attack and the aircraft will exhibit large pitch angles during take-off and landing.

Hybrid flying wing (HFW)

It was realized that a concept with roughly equal useful volumes in fuselage and wing could have superior aerodynamic performance compared to the presently dominant layout. Moreover, several problems inherent to the BWB could be avoided: the family concept, potential emergency egress, passenger comfort. A very provisional geometry was conceived, which appeared to have a wetted area halfway between the traditional a/c and the BWB. Its aerodynamic performance was some 10% less than the TsAGI design, but this is probably due to the smaller span (90m).

Spanloader **(p.t.o.)**

Looking at all these flying wings it was realized that NASA initiated several study projects during the seventies to investigate the properties of very large dedicated freighter designs with flying wing layout. These designs had non-tapered wings containing a large number of standard containers, featuring loading doors at the wing tips. A very sketchy freighter design was conceived according to the principles of these NASA studies. It was found that a practical geometry could be obtained with a wing area of 2,000m^2 and 95m span. In spite of the low aspect ratio (A=4.5) this design has similar aerodynamic performance, although the Mach number was reduced to 0.75. Its main advantages, however, are the enormous freighthold volume – twice as big as the tapered all-wing a/c – that can be loaded quite easily. The spanwise distribution of its useful load leads to a very considerable reduction of the bending moment and.

Conclusions (see the slides)