BLENDED WING BODY AND ALL-WING AIRLINERS

EGBERT TORENBEEK

European Workshop on Aircraft Design Education (EWADE)
Samara, Russia, May/June 200
PIAGGIO P-180 AVANTI (1986)
THE DOMINANT GENERAL ARRANGEMENT

BOEING 707 (1954)
DREAMLINER

BOEING 787 (2007)
EFFICIENCY OF FUEL ENERGY CONVERSION

Seat-kilometer per liter fuel: \( \frac{H \eta L/D}{W_{to}/N} \)

- \( H \) - fuel heating value per liter
- \( \eta \) - efficiency of energy conversion
- \( L/D \) - glide ratio
- \( W_{to}/N \) - aircraft all-up weight per seat
MAIN CONFIGURATION CHOICES

PRIMARY
• NUMBER AND LONGITUDINAL DISPOSITION OF LIFTING SURFACES
• ALLOCATION OF USEFUL VOLUME (PAYLOAD, FUEL) IN WING AND FUSELAGE(S)
• PROPULSION SYSTEM CLASS (TURBOFAN, TURBOPROP, DUCTED ROTOR)

SECONDARY
• VERTICAL DISPOSITION OF LIFTING SURFACES
• LOCATION OF ENGINES
<table>
<thead>
<tr>
<th>canard</th>
<th>tandem</th>
<th>classical</th>
<th>three-surface</th>
<th>joint wing</th>
<th>tailless</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="canard" /></td>
<td><img src="image" alt="tandem" /></td>
<td><img src="image" alt="classical" /></td>
<td><img src="image" alt="three-surface" /></td>
<td><img src="image" alt="joint wing" /></td>
<td><img src="image" alt="tailless" /></td>
</tr>
<tr>
<td>twin fuselage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="twin fuselage" /></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-wing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="C-wing" /></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>blended wing body</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="blended wing body" /></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>all wing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="all wing" /></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

DASA (modified)
SINGLE AND TWIN FUSELAGE WING BENDING

- 100%
- 43%

- Lift distribution
- Mass distribution
- Bending moment distribution
# TWIN FUSELAGE WEIGHT REDUCTIONS

<table>
<thead>
<tr>
<th>Design mass, kg</th>
<th>conventional</th>
<th>twin-fuselage</th>
<th>Δ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTOW</td>
<td>155,000</td>
<td>134,000</td>
<td>-13.5</td>
</tr>
<tr>
<td>MLW</td>
<td>128,000</td>
<td>113,000</td>
<td>-11.7</td>
</tr>
<tr>
<td>MZFW</td>
<td>120,000</td>
<td>106,000</td>
<td>-11.7</td>
</tr>
<tr>
<td>OEW</td>
<td>84,000</td>
<td>70,000</td>
<td>-16.7</td>
</tr>
<tr>
<td>Payload (structural limit)</td>
<td>36,000</td>
<td>36,000</td>
<td>0</td>
</tr>
<tr>
<td>Block fuel for 8,000 km</td>
<td>40,715</td>
<td>34,245</td>
<td>-15.9</td>
</tr>
<tr>
<td>Installed thrust, kN</td>
<td>2x222.5</td>
<td>2x178.0</td>
<td>-20.0</td>
</tr>
</tbody>
</table>
AERODYNAMIC EFFICIENCY

\[
(L/D)_{\text{max}} = \frac{1}{2} \sqrt{\frac{b}{S_{\text{wet}}}} \sqrt{\frac{\pi e}{C_{D_{\text{wet}}}}} = \frac{1}{2} \sqrt{\frac{\pi Ae}{(C_D S)_{\text{wet}}/S}}
\]

- \(b\) - wing span
- \(e\) - Oswald’s span efficiency factor
- \(S_{\text{wet}}\) - total surface area exposed to flow
- \(C_{D_{\text{wet}}}\) - profile and parasitic drag coefficient based on \(S_{\text{wet}}\)
WING SHAPE AND SPAN EFFICIENCY

\[ e \equiv \text{span efficiency factor for induced drag} \]

- biplane: \( e = 1,36 \)
- X-wing: \( e = 1,33 \)
- split tips: \( e = 1,32 \)
- end plates: \( e = 1,38 \)
- box wing: \( e = 1,46 \)
- joint tips: \( e = 1,05 \)
- C-wing: \( e = 1,45 \)
- winglets with endplates: \( e = 1,20 \)
- winglets: \( e = 1,41 \)
- large dihedral: \( e = 1,03 \)

rear view
BOEING C-WING

Dimensions:
- Length: 72.6 m
- Wing Span: 66 m
- Height: 17 m
LOCKHEED BOX WING
It has long been recognized that the flying wing, when jet propelled, is a poor choice for an aircraft configuration intended to achieve long range (J.V.Foa 1984)
CONVENTIONAL AND FLYING WING COMPARED

Useful load volume $2,000 \text{ m}^3$, $M = 0.82$

Conventional configuration, $(L/D)_{\text{max}} = 20.6$

Flying wing, $(L/D)_{\text{max}} = 25.7$
WING PLUS BODY COMBINATIONS WITH THE SAME TOTAL VOLUME

WING ASPECT RATIO 8

<table>
<thead>
<tr>
<th>WING VOLUME</th>
<th>TOTAL VOLUME</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>0.85</td>
<td>0.85</td>
</tr>
</tbody>
</table>
BASIC ASSUMPTIONS

• WING / BODY COMBINATIONS ARE COMPARED FOR CONSTANT TOTAL USEFUL VOLUME AND WEIGHT
• AERODYNAMIC PERFORMANCE IN CRUISING FLIGHT IS USED AS FIGURE OF MERIT TO COMPARE DIFFERENT VOLUME ALLOCATIONS
• DRAG DUE TO TAILPLANES, INTERFERENCE, ROUGHNESS, AND EXCRESCENCES ARE ACCOUNTED FOR BY MULTIPLICATION FACTORS
• POWERPLANT INSTALLATION DRAG IS ACCOUNTED AS A REDUCTION OF INSTALLED THRUST
DEFINITIONS

VOLUME ALLOTMENT RATIO X

\[ X = \frac{\text{USEFUL VOLUME INSIDE WING}}{\text{TOTAL USEFUL VOLUME}} = \frac{Q_w}{Q_{\text{tot}}} \]

BODY VOLUME:

\[ Q_b = (1 - X) Q_{\text{tot}} = \left(\frac{1}{X} - 1\right) Q_w \quad ; \quad 0 < X \leq 1 \]

FLYING WING, THEORETICALLY: \( X = 1 \)

APPROXIMATION FOR "WET" WINGS:

\[ X \approx \frac{\text{VOLUME WING FUEL TANKS}}{\text{VOLUME (tanks + cabin + freighthold)}} \]

TYPICAL VALUES FOR CONVENTIONAL LONG-RANGE JET TRANSPORTS:

\[ X = 0.15 \text{ TO } 0.20 \]

SHAPE FACTOR \( k_{bw} \)

\[ k_{bw} = \frac{c_D b}{c_D w \left(\frac{\eta_w}{\eta_b}\right)^{2/3}} \]

\[ b = \text{BODY} \]
\[ w = \text{WING} \]

\[ \bar{c}_D = \frac{\text{ZERO-LIFT DRAG AREA}}{(\text{ENCLOSED VOLUME})^{2/3}} = \frac{C_D S}{Q^{2/3}} \]

\[ \eta_w, \eta_b = \frac{\text{(NET USEFUL VOLUME)}}{\text{(GROSS) ENCLOSED VOLUME}} \]

TYPICAL NUMERICAL VALUE: \( k_{bw} = 1/4 \text{ TO } 1/3 \)

PHYSICAL MEANING:

\[ k_{bw} = \frac{\text{BODY (PARASITE) DRAG}}{\text{WING (PROFILE) DRAG}} \quad \text{for } Q_w = Q_b \]

A wing has three to four times the drag of a fuselage with the same useful volume. This is due to the more favorable ratio of wetted area to volume for streamline bodies of revolution, compared to the two-dimensional wing.
\[
\frac{C_D}{C_L} = \frac{C_{Dp}}{C_L} \left[ 1 + k_{bw} \left( \frac{1}{X} - 1 \right)^{2/3} \right] + \beta C_L
\]

WHERE \( C_{Dp} \) = WING PROFILE DRAG COEFFICIENT
\( \beta = \frac{u}{\sqrt{C_L}} \)

FOR GIVEN
- * ALL-UP WEIGHT \( W \)
- * DYNAMIC PRESSURE \( q = \frac{1}{2} \gamma p M^2 \)
- * TOTAL VOLUME \( Q_{tot} \)

THE LIFT COEFFICIENT IS:

\( C_L = C_{L_{X=1}} X^{-2/3} \)

WHERE \( C_{L_{X=1}} \) DENOTES THE LIFT COEFFICIENT OF A FLYING WING WITH VOLUME \( Q_{tot} \)

HENCE THE LIFT/DRAG RATIO IS OBTAINED FROM:

\[
\frac{C_D}{C_L} = \frac{C_{Dp}}{C_{L_{X=1}}} \left[ X^{2/3} + k_{bw} (1 - X)^{2/3} \right] + \beta C_{L_{X=1}} X^{-2/3}
\]
L/D AFFECTED BY ALTITUDE

AUW 4,500 kN; total gross volume 2,000 m³; Mach 0.8; A=8

(L/D)_{max}
L/D AFFECTED BY AVAILABLE THRUST

AUW 4,500 kN; total gross volume 2,000 m$^3$; $M=0.8$; $A=8$
L/D AFFECTED BY ASPECT RATIO

AUW 4,500 kN; total gross volume 2,000 m$^3$; M=0.8 @ 35,000ft
INITIAL OBSERVATIONS

• FOR GIVEN FLIGHT CONDITION THE HIGHEST L/D IS OBTAINED FOR EITHER A FLYING WING OR A DISCRETE WING/BODY CONFIGURATION
• FOR SPECIFIED INSTALLED ENGINE THRUST THE HIGHEST L/D IS GENERALLY OBTAINED FOR A WING/BODY COMBINATION
• THE ASPECT RATIO HAS A MAJOR EFFECT ON L/D FOR WING/BODY COMBINATIONS
• ALL-WING AIRCRAFT DO NOT GAIN FROM A HIGH ASPECT RATIO
ALL-WING AIRCRAFT

- The volumetric capacity in relation to wetted area tends to be unfavourable compared to conventional A/C
- For typical transonic cruise altitude and speed all-wing A/C do not achieve the highest aerodynamic performance
- The best performance is achieved for high altitudes and low air speeds
- High aspect ratio is not helpful
TRANSFORMATION OF A BALL INTO AN AIRCRAFT

660 m² → 2,100 m² → 3,400 m²

3,750 m² → 4,250 m²
AIRCRAFT SHAPED AS A BEERMAT

660 m²
2,000 m²
2,750 m²
2,850 m²
3,000 m²
EARLY MDD/BOEING BWB DESIGN

800 passengers
7,000 nm range
span 280 ft
cruise L/D = 23

RECENT (SMALLER) BWB DESIGN HAS THE PASSENGER CABIN ON ONE UPPER DECK
HIGH MACH NUMBER BWB CONFIGURATIONS
SYNERGY OF BASIC BWB COMPONENTS

- Passenger cabin shape, freighthold and fuel tank allocations are strongly interrelated.
- The fuselage is also a wing and a pitch control surface, engines may be buried inside.
- Vertical surfaces provide directional stability/control, and act as winglets.
- Synergy reduces total wetted area by 30%, typically, relative to conventional layout with the same useful load.
THE UNUSUAL BWB DESIGN PROCESS

• THE INTERACTION OF THE BASIC DISCIPLINES (AERO, STRUCTURES, WEIGHT AND BALANCE) IS UNUSUALLY STRONG

• CONVENTIONAL DESIGN INTUITION AND APPROACH ARE CHALLENGED

• A SLIGHT CHANGE IN PLANFORM LEADS TO A COMPLETE RECONFIGURING OF THE ENTIRE VEHICLE

• THE BWB MUST BE SELF-BALANCED IN ORDER TO AVOID HIGH TRIM DRAG DUE TO CONTROL DEFLECTION
TYPICAL LARGE BLENDED WING BODY

TYPICAL LARGE BLENDED WING BODY

42.6 m

90 m
CHALLENGES FOR THE BWB CONCEPT

• STRUCTURAL DESIGN OF THE PRESSURE CABIN DUE TO ITS NON-OPTIMUM CROSS SECTION
• STRETCHING OR SHRINKING MUST TAKE PLACE LATERALLY (SPANWISE) IN HEAVILY LOADED AND NON-CYLINDRICAL STRUCTURE
• PASSENGER ACCEPTANCE OF WINDOWLESS CABIN AND HIGH ANGLES OF ATTACK DURING TAKE-OFF AND LANDING
• RIDE QUALITY DURING GUSTS AND MANEUVERS
• NEW EMERGENCY EVACUATION RULES REQUIRED
TsAGI HYBRID CONFIGURATION
HYBRID FLYING WING AND SPAN-LOADER
5 CONFIGURATIONS COMPARED

<table>
<thead>
<tr>
<th></th>
<th>Volume m³</th>
<th>Wetted area m²</th>
<th>(L/D)$_{\text{max}}$ subcritical</th>
<th>C$_L$ cruise</th>
<th>L/D cruise</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONVENTIONAL</td>
<td>3,262</td>
<td>3,852</td>
<td>20.6</td>
<td>0.47</td>
<td>19.7</td>
</tr>
<tr>
<td>ALL-WING</td>
<td>3,319</td>
<td>3,562</td>
<td>25.7</td>
<td>0.24</td>
<td>23.2</td>
</tr>
<tr>
<td>BLENDED WING BODY</td>
<td>3,025</td>
<td>3,040</td>
<td>26.1</td>
<td>0.28</td>
<td>24.4</td>
</tr>
<tr>
<td>HYBRID FLYING WING</td>
<td>3,230</td>
<td>3,445</td>
<td>24.5</td>
<td>0.36</td>
<td>22.7</td>
</tr>
<tr>
<td>SPANLOADER</td>
<td>6,700</td>
<td>4,800</td>
<td>24.0</td>
<td>0.26</td>
<td>22.1</td>
</tr>
</tbody>
</table>

Approximately equal useful load, cruise speed and altitude
CONCLUSIONS – BLENDED WING BODY

- **THE BWB FORMS A NEW CATEGORY BETWEEN CONVENTIONAL AND ALL-WING CONFIGURATIONS**
- **IT IS CHARACTERIZED BY A LOW ASPECT RATIO HIGH THICKNESS RATIO INBOARD WING, A HIGH ASPECT RATIO OUTBOARD WING, AND BASIC VERTICALS**
- **A BWB HAS THE POTENTIAL OF ACHIEVING THE SAME OR BETTER AERODYNAMIC QUALITY AS ALL-WING AIRCRAFT, FOR SMALLER WING SPAN**
- **WING LOADING AND CRUISE CONDITIONS ARE WELL TEMPERED**
- **CRUISE L/D RATIO IMPROVEMENTS UP TO 25% ARE POSSIBLE, FUEL AND INSTALLED THRUST SAVINGS ARE EVEN HIGHER**
IS THERE A FUTURE FOR THE BWB?

• INDUSTRIAL AND OPERATIONAL REALIZATION WILL ENTAIL SIGNIFICANT CHALLENGES
• MOST DOUBTS ARE ASSOCIATED WITH PASSENGER ACCEPTANCE
• A VERY LARGE CIVIL OR MILITARY FREIGHTER SEEMS TO HAVE THE BEST CHANCE OF REALIZATION