MDO of Forward Swept Wings

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Warning: this presentation contains

70% Motivation for Design and Optimization
20% Monodisciplinary Design and Optimization
10% Multidisciplinary Design and Optimization

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Motivation

➤ Fuel price is likely to grow faster than other components of total operating costs.
  ➤ Higher technology costs will become more acceptable with higher fuel prices.
  ➤ Low drag and lightweight structures are design drivers.

➤ Effect of aviation on environment must be constrained.
  ➤ Soon: additional costs due to CO$_2$ emissions.
  ➤ Low drag aircraft burn less fuel, produce less CO$_2$, NO$_x$, soot, ...
L/R DOC Sensitivity for Fuel Price Development

Oil price hit 100 $/Barrel for the first time on Jan 3rd 2008!

Oil Prices, 1994-2007

NYMEX Light Sweet

Based on A330-200 type aircraft with 1990 technology

Capital Costs
Insurance
Landing fees
Navigation
Flight crew
Line maintenance
Engine maintenance
Airframe maintenance
Fuel

5 $/USgal

+104%

2 $/USgal

+28%

0.9 $/USgal
Drag Reduction Technologies

- Many technologies have been and are examined
  - Laminar flow,
    distributed roughness, bumps,
    dimples, plasma, synthetic jets, ...

- Laminar flow technology is the only single technology with the potential to reduce drag and hence fuel consumption considerably.

- Snowballing effects add to the effect of pure drag reduction and pay off in lower mass.

- NLF or HLF with simplified suction systems are feasible.

- Operational aspects (loss of laminarity) can be handled similar to ETOPS.

- The potential of laminar flow technology is big:
  - 15 - 20% overall aircraft drag reduction feasible
Drag Reduction – Where?

Drag distribution on aircraft level

Total Drag

Friction Drag

Parasite

Wave / Interference

Lift Dependent Drag

Friction Drag

Pylons + Fairings

Nacelles

Horizontal Tail

Vertical Tail

Wing

Fuselage

> Wing offers (besides fuselage) highest potential for friction drag reduction
Drag Reduction Potential for A340

Benefits: Lower fuel burn
- decreased pollution
- decreased CO₂
- range extension
- reduced DOC

Savings (aircraft level):
- Wing: - 12%
- Tail: - 3%
- Nacelles: - 1%

10% net drag reduction is targeted for application of laminar flow technology

Example Standard Long Range Mission:
Frankfurt → New York (~3340 NM; ~54 t fuel consumption)
Saving 10 % fuel ≈ 5,4 t!
Boundary Layer Transition Mechanisms

- Main drivers are
  - Reynolds number
  - velocity/pressure/Mach distribution $\rightarrow$ airfoil shape
  - wing sweep $\rightarrow$ leading edge sweep angle

<table>
<thead>
<tr>
<th>Transition Mechanism</th>
<th>straight wing</th>
<th>swept wing</th>
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<td>Tolmien Schlichting Instability</td>
<td>X</td>
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<tr>
<td>Crossflow Instability</td>
<td>-</td>
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<td>Attachment Line Transition</td>
<td>-</td>
<td>X</td>
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Tapered Swept Wings

- Transition on swept wings is affected strongly by leading edge sweep angle ($\phi_{0\%}$).

- Chordwise position of transition depends on $Re_T$ and pressure recovery.

$$Re_T = Re \cdot \frac{x_T}{c}$$

- For transonic aerodynamics the relevant sweep is not at the leading edge ($\phi_{0\%}$) or at the 25% chord line ($\phi_{25\%}$), but more close to the 50% chord line ($\phi_{50\%}$, typical location of shock).

- The taper ratio affects sweep angle of leading and trailing edges.
Geometry of Tapered Swept Wings

- BSW
- $\phi_{LE}$ is larger than $\phi_{50\%}$
Geometry of Tapered Swept Wings

- BSW
  - $\phi_{LE}$ is larger than $\phi_{50\%}$

- FSW
  - $\phi_{LE}$ is smaller than $\phi_{50\%}$
Laminar Flow Limits for Swept Wings

What has been achieved?

- Natural Laminar Flow
  - LFC - B-18, slotted glove, flight tests
  - 6-series airfoils, Langley LPTP tests
  - LFC - RAE Vampire, flight tests
  - King Cobra, flight test
  - Ames 12-ft wind tunnel tests
  - NLF - F-111/TACT flight test
  - NLF - Boeing 757 glove flight test
  - NLF - F-14 VSTFE flight test, M=0.6 ... 0.8
  - NLF - F-15, flight test, M=0.9 ... 1.2
  - NLF - ELFIN A320 fin 50%, S1MA, M=0.7
  - HLF - ELMFIN A320 fin, flight test, M=0.78
  - HLF - ELMFIN A320 fin, simplified system, M=0.78

- Hybrid Laminar Flow
  - LFC - RAE Vampire, flight tests
  - NLF - F-15, flight test, M=0.9 ... 1.2
  - HLF - ELMFIN A320 fin 50%, S1MA, M=0.7
  - HLF - ELMFIN A320 fin, flight test, M=0.78
  - HLF - ELMFIN A320 fin, simplified system, M=0.78
  - BSW Reference x_t ≈ 12% c
  - FSW x_t ≈ 25% c
Natural Laminar Flow on Swept Wings

- Typical cruise case.
- Conservative.
- Shaded areas show laminar flow.
- Light blue (bottom) when LE sweep is reduced to 11°.

Natural Laminar Flow

- cruise altitude: 10 km
- cruise Mach number: 0.8
- airfoil pressure recovery at: 65%
Some historic Forward Swept Wing Designs

Alexander Lippisch
1935: DFS 42 “Kormoran”
Some Historic Forward Swept Wing Designs

Hans Wocke
1942: Junkers 287
1946: EF 131, 140 (Russia)
1970: HFB 320 “Hansa Jet”
(over 50 built)
Some Historic Forward Swept Wing Designs

Bell
1945: X-1
(test configuration)
Some Historic Forward Swept Wing Designs

W. P. Tsybin
1947: LL-3
Some Historic Forward Swept Wing Designs

Grumman
1985: X-29
2000: Suchoi S-37
Summary of Historic Forward Swept Wing Designs

- First FSW designs during the 1940s.
- Some activity around 1945-1946 in USSR and USA.
- FSW concept revitalized in the 1980s for military aircraft:
  - X-29 (1985), S-37 “Berkut” (2000) built, flight tested,
  - improved $C_{L_{max}}$, maneuver performance.
- FSW with Laminar Flow
  - V-Jet (no business success),
  - two seater sailplanes.
Flow Field of Swept Wings

- Comparison of wings having different sweep angles.
- All wings have the same spanwise lift distribution (e.g. elliptical).
- All wings have the same induced drag.
- All wings have the same spanwise bending moment distribution.
Flow Field of Swept Wings

- All wings have the same mean downwash velocity.
- Sweep affects the spanwise downwash distribution.
Flow Field of Swept Wings

- All wings have the same induced drag.
- Sweep affects the spanwise drag distribution.
- BSW has thrust at tips.
- FSW has thrust at root.
Aerodynamics of Tapered Swept Wings

- Tapered FSW needs less twist to achieve reasonable lift coefficient distribution.

- Off-design effects:
  - Increased angle of attack (takeoff/landing) → additional lift.
  - Backward swept wing: → additional lift in outboard wing, → tip stall.
  - Forward swept wing: → additional lift in center wing, → root stall.
Design of Forward Swept Wings

Activities at DLR
- First studies in 1990s.
- National research program LuFo 2005-2007:
  - Design of backward swept, turbulent reference wing
  - Design of a forward swept, turbulent wing
  - Design of a forward swept, laminar wing
  - Application of FSW to low noise aircraft configuration.
Multidisciplinary Optimization of Forward Swept Wings

Graphics courtesy Ulrich Herrmann.

MDO-Optimization of M=1.6 transport aircraft.
Design of Forward Swept Wings

- Mono-Disciplinary Design & Optimization procedure applied at DLR in national project (LuFo/K2020):
  - Selection of planform (e.g. based on preliminary design).
  - Definition of a matching wing body configuration.
  - Selection of suitable basic airfoil sections.
  - Application of Navier-Stokes solver.
  - Design loop:
    - numerical black box optimization of twist distribution.
    - inverse 3D wing design \(\rightarrow\) adapted airfoil sections.
    - repeat cycle until satisfied.

- No structural constraints applied \(\rightarrow\) approx. elliptical lift distribution.
Design and Integration of Forward Swept Wings

- Typical startup difficulties.
- Wing root in upwash field needs
  - careful design,
  - twist, nose shape,
  - new belly fairing philosophy.

- bad initial design:
  - flow separation at root.
Design and Integration of Forward Swept Wings

- Optimization of a BSW reference wing:
  - \( M = 0.8, \phi_{0\%} = 31^\circ, \phi_{50\%} = 24^\circ. \)
- Optimization of a FSW reference wing:
  - \( M = 0.8, \phi_{0\%} = 16^\circ, \phi_{50\%} = 24^\circ. \)
- L/D of both turbulent wings favor FSW:
  - \( \text{L/D}_{\text{wing, BSW}} = 26.0 \quad \text{L/D}_{\text{wing, FSW}} = 27.5. \)

Results courtesy Judith von Geyr.
Future Multidisciplinary Approach

Develop suitable objectives and constraints:
- performance based → drag, mass (design, off-design),
- stiffness based → divergency, aileron reversal, flutter,
- geometry based → thickness distribution.

Use high fidelity methods for accurate modeling:
- aerodynamics:
  - model transonic effects (Euler, Navier-Stokes),
  - model transition (TS and CF stability analysis, ALT criterion?),
  - suction distribution (for HLF design).
- structures:
  - finite element models,
  - structural sizing,
  - elastic tailoring (metal, composite).

Perform coupled optimization:
- aeroelastic equilibrium.
MDO chain for transonic Wing optimization

- Global Level Optimizer
  - Gradient free approach (e.g. Simplex type)
- Surface Geometry Generator
  - Flight shape
  - Parametric CAD model (CATIA V5)
- Parametric Structure Geometry Generator
  - Realistic rib-spar design
  - Stringers modeled by stiffness equivalent layers
- Aerodynamic Analysis
  - CFD code in inviscid mode (TAU)
  - Viscous drag estimation (flat plate)
- Structural-Sizing
  - Multiple load cases (Fatigue 1.0g, maneuver 2.5g, Touch Down 1.2g)
  - FEM solver (ANSYS)
  - Optimizer/Sizing (ANSYS)
Multi Disciplinary Optimization Process

- DLR Project TIVA – Technology Integration for the Virtual Aircraft
- Objectives:
  - assessment of technologies in the context of the complete aircraft,
  - connecting models, people.
- Desired features:
  - multi-disciplinary, - fidelity, - site,
  - common aircraft description for all disciplines,
  - usage of existing legacy as well as new codes,
  - allowing for freedom of concept selection,
  - allowing for versioning, authorization etc.
- Evaluation of several in-house and commercial frameworks.
  - Further development using commercial framework “ModelCenter”.
Multi Disciplinary Optimization Process

- Typical process chain for an UAV.
- Each tool is wrapped and can reside locally or on a server.
- Tools are linked by variables/data streams.
- Tools are only executed when needed.
Multi Disciplinary Optimization Process

- Single aircraft description „CPACS“
- Simple example: wing geometry
- Automatic generation of:
  - Lists and reports (XSLT),
  - simple 2D-views,
  - simple CAD model Rhinoceros,
  - parametric CAD model CATIA V5,
  - aero method VSAERO,
  - … up to Hi-Fi methods.
Multi Disciplinary Optimization Process

- Much effort was spent in defining a common aircraft description (this is an ongoing process).

- Such a description is of course limited, cannot be completely general.

- Basic modules are currently being adapted:
  - Aerodynamics (→ performance),
  - Engines (→ performance, emissions),
  - Structures (→ stiffness, → mass),
  - Flight simulation (→ stability & control, handling qualities),
  - Noise (→ shielding, trajectory),
  - Environmental impact (→ CO₂, NOₓ, contrails),
  - Mission simulation.
Finally – Optimization Wish List

More intelligence
- multi-level optimization techniques (e.g. BLISS),
- multi-algorithmic optimization (mix of optimizers).

More efficiency
- parallelized optimizers:
  - gradient & gradient-free algorithms:
    - concurrent evaluation of gradients,
    - concurrent search from different starting points.
  - genetic:
    - concurrent evaluation of objective.

Follow hardware development
- make better use of PC clusters,
- make better use of multi-core processors (2-8 threads in parallel).

Note: Some of these items are available in software like ModelCenter/CenterLink.
If you cannot decide...