MDO of Forward Swept Wings

KATnet II Workshop, 28-29 January 2008, Braunschweig

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Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

MDO of Forward Swept Wings

Warning: this presentation contains

70% **Motivation for Design and Optimization**

20% **Monodisciplinary Design and Optimization**

10% **Multisciplinary Design and Optimization**

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DLR Institute of Aerodynamics and Flow Technology, Braunschweig

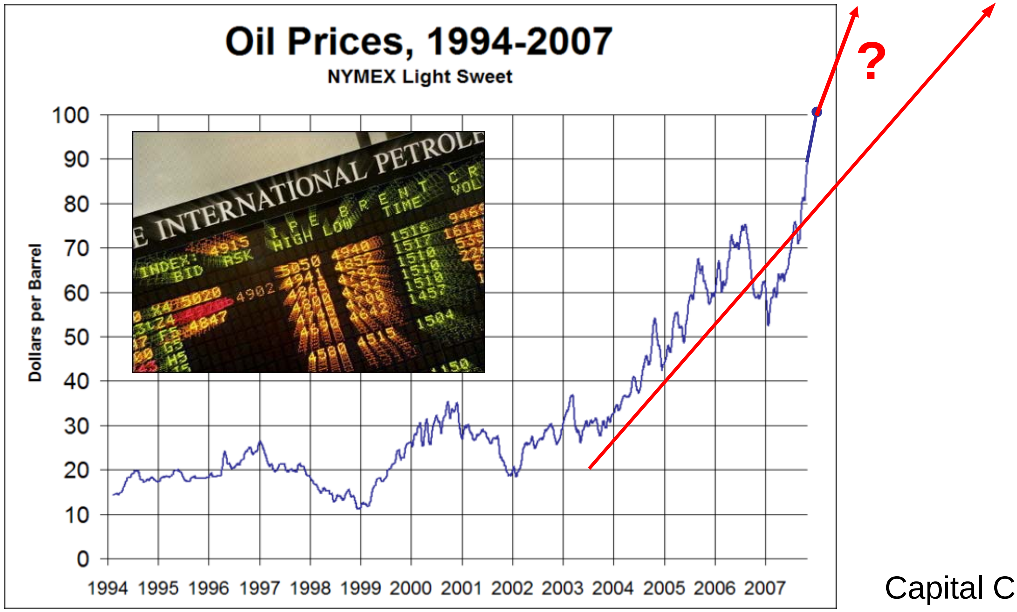
Motivation

- 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.

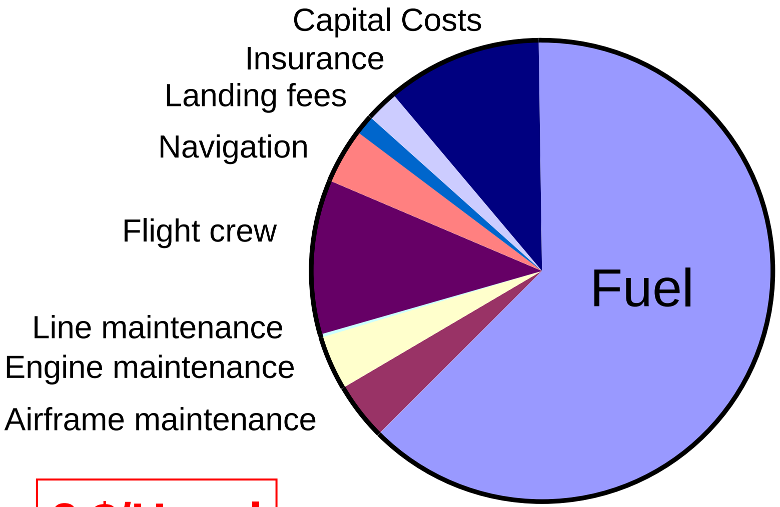
- Effect of aviation on environment must be constrained.
    - Soon: additional costs due to CO_2 emissions.
    - Low drag aircraft burn less fuel, produce less CO_2, NO_x soot, ...

L/R DOC Sensitivity for Fuel Price Development

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

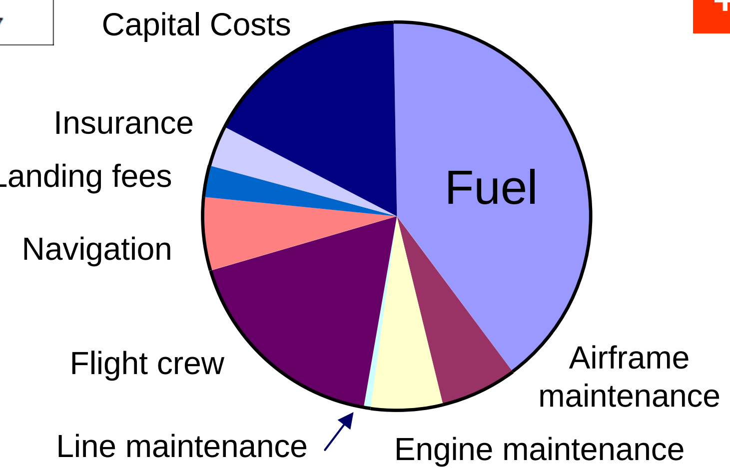


5 $/USgal



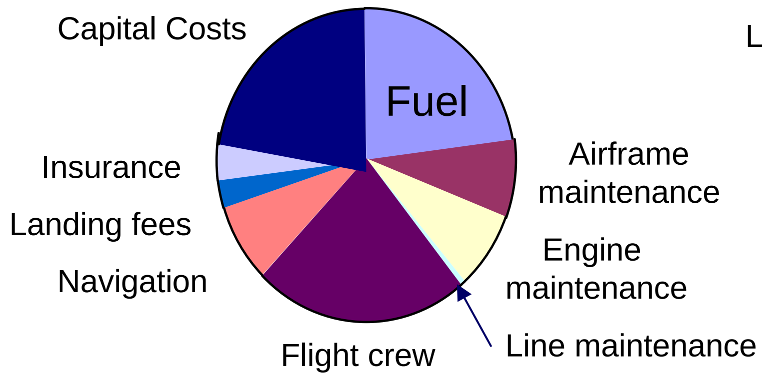
+104 %

2 $/Usgal



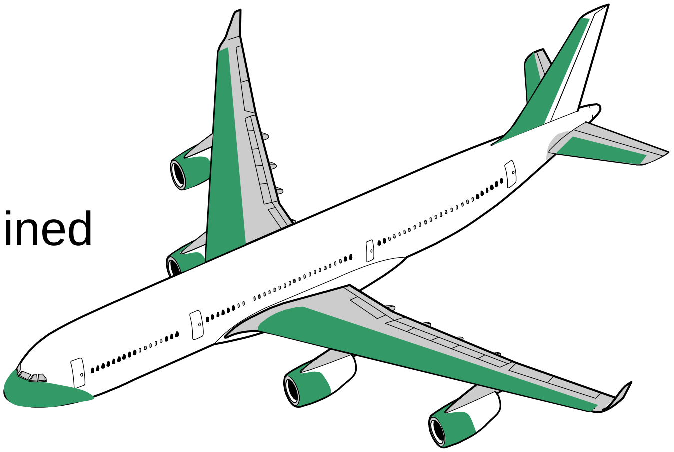
+28 %

0.9 $/Usgal



based on A330-200 type a/c with *1990* technology

Drag Reduction Technologies



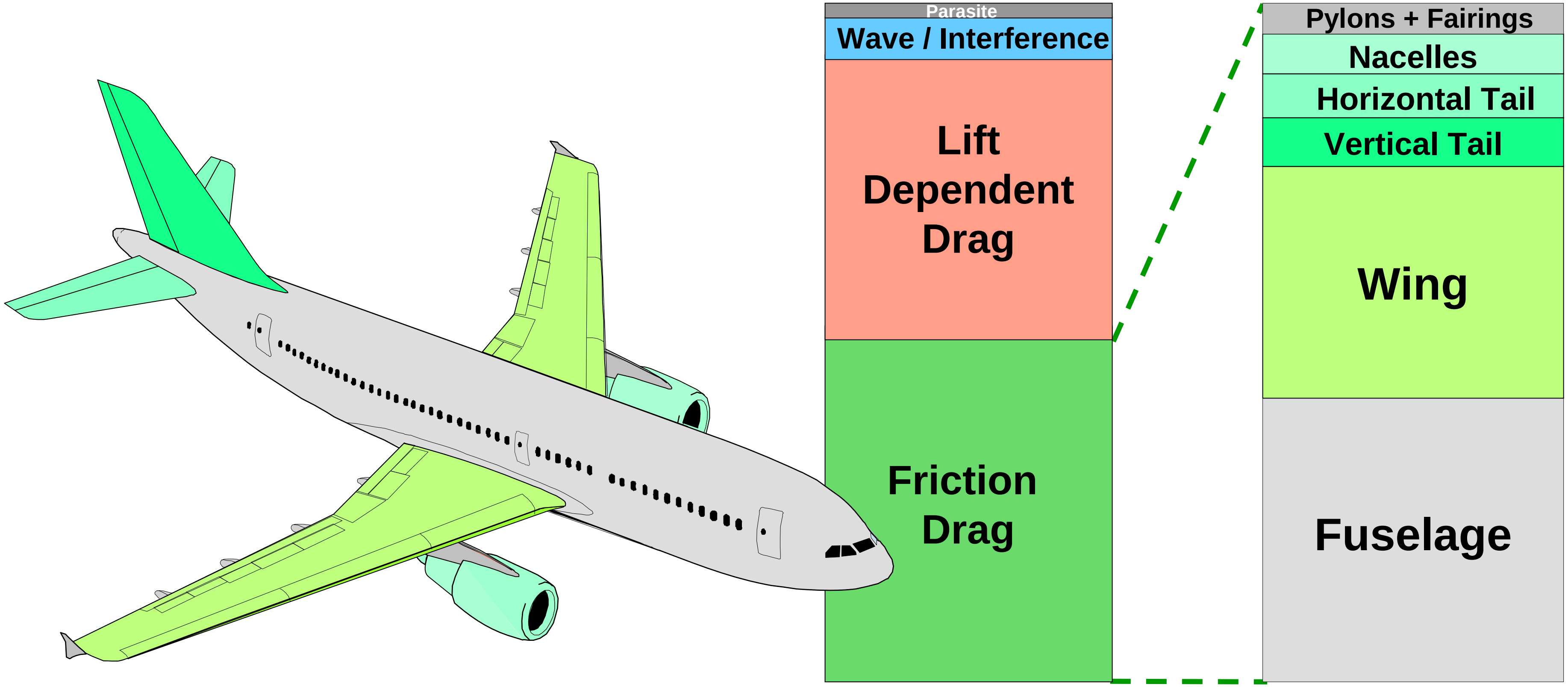
- Many technologies have been and are examined
  - Laminar flow,
    distributed roughness, bumps,
    dimples, plasma, synthetic jets, ...
- Laminar flow technology is the only <u>single</u> technology with the potential to reduce drag and hence fuel consumption <u>considerably</u>.
- Snowballing effects 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

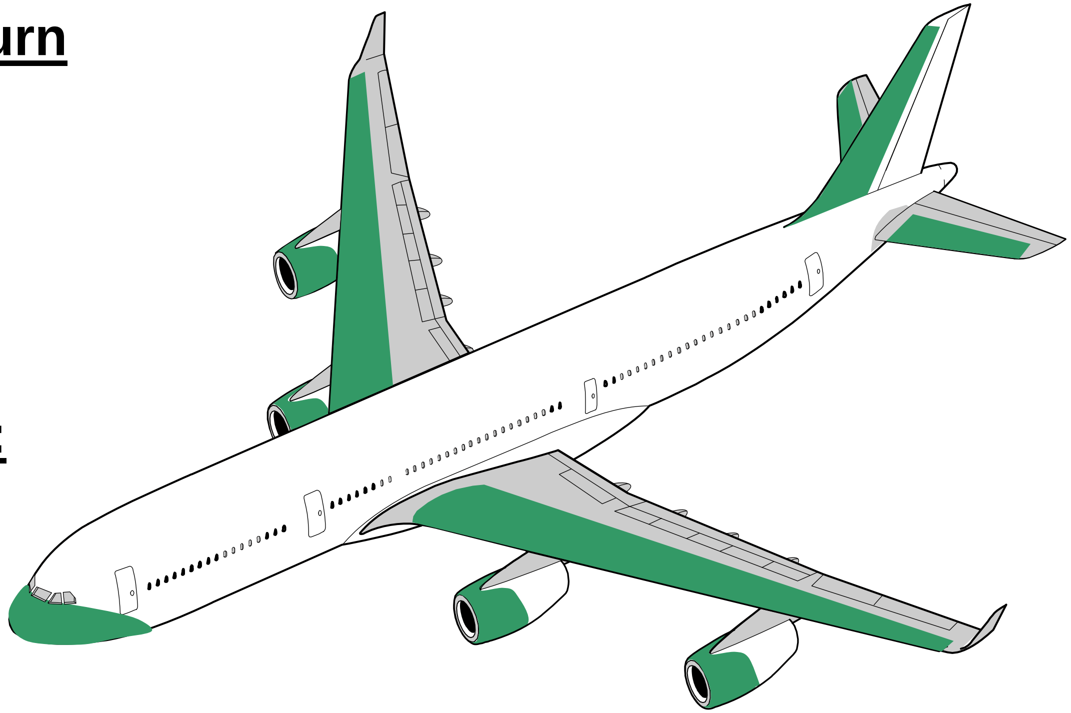
Total Drag

Friction Drag



> Wing offers (besides fuselage) **highest potential for friction drag reduction**

Drag Reduction Potential for A340



Benefits: Lower fuel burn

- decreased pollution
- decreased CO_2
- 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 → airfoil shape
  - wing sweep → leading edge sweep angle

Transition Mechanism	straight wing	swept wing
Tolmien Schlichting Instability	X	X
Crossflow Instability	-	X
Attachment Line Transition	-	X

Tapered Swept Wings

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

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

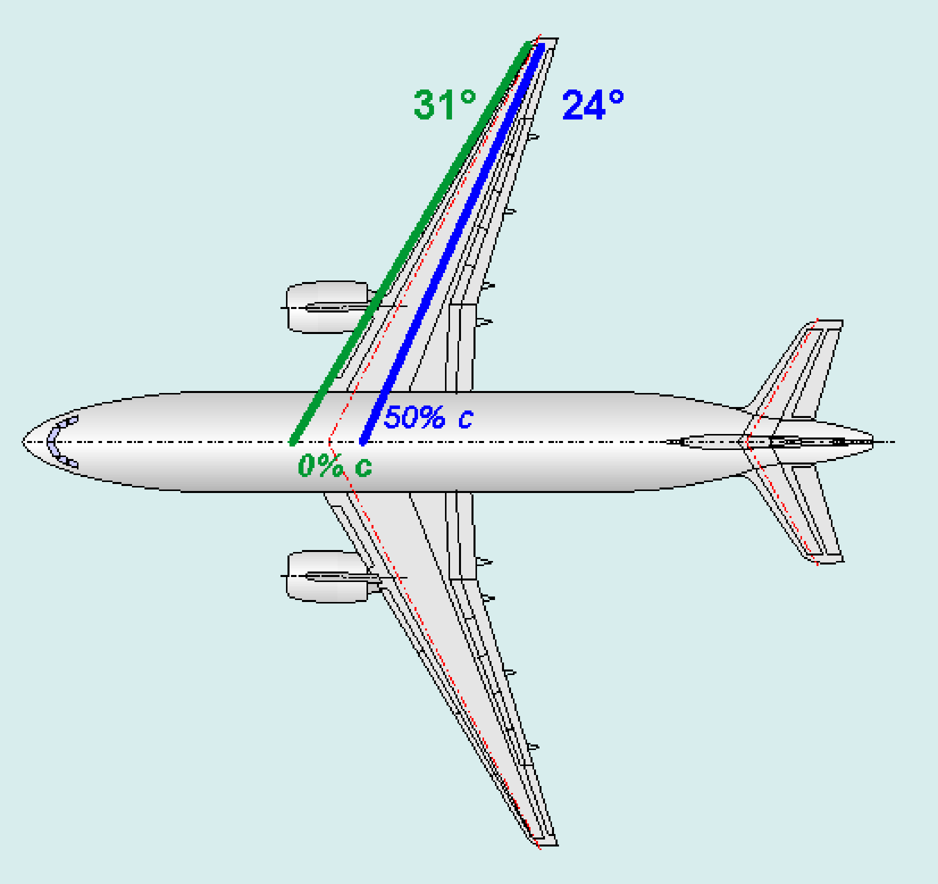
$$Re_T = Re \cdot \frac{x_T}{c}$$

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

- The taper ratio affects sweep angle of leading and trailing edges.

Geometry of Tapered Swept Wings

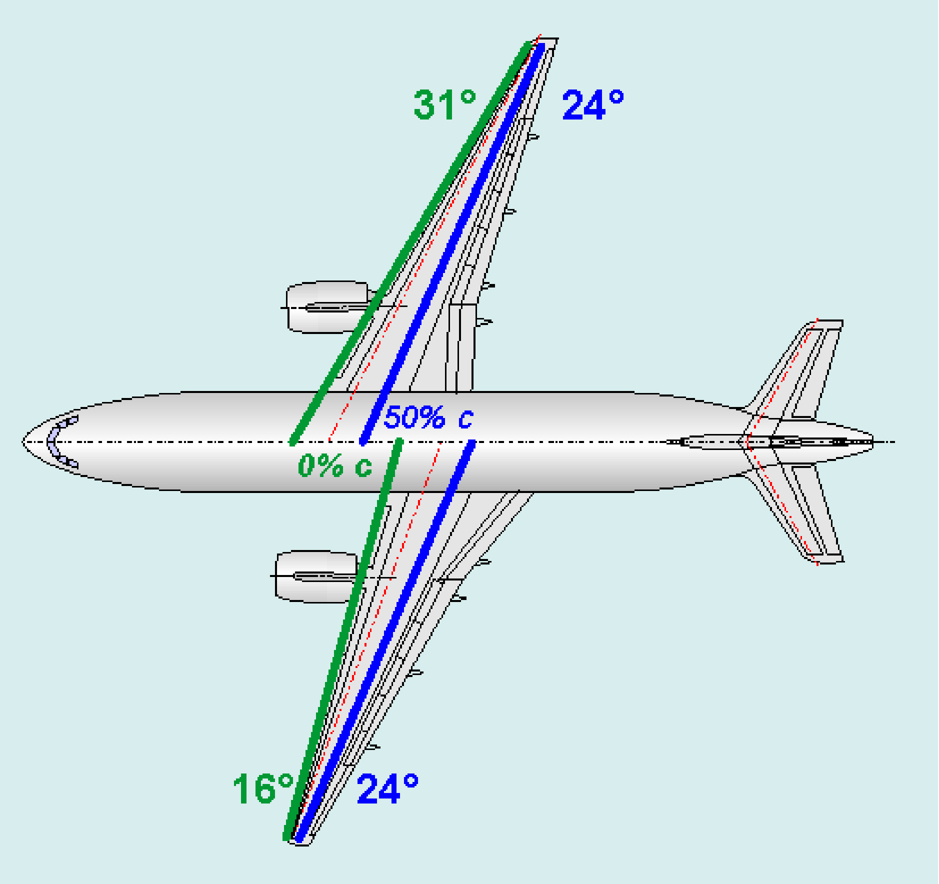
- BSW
- φ_{LE} is larger than $\varphi_{50\%}$



Geometry of Tapered Swept Wings

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

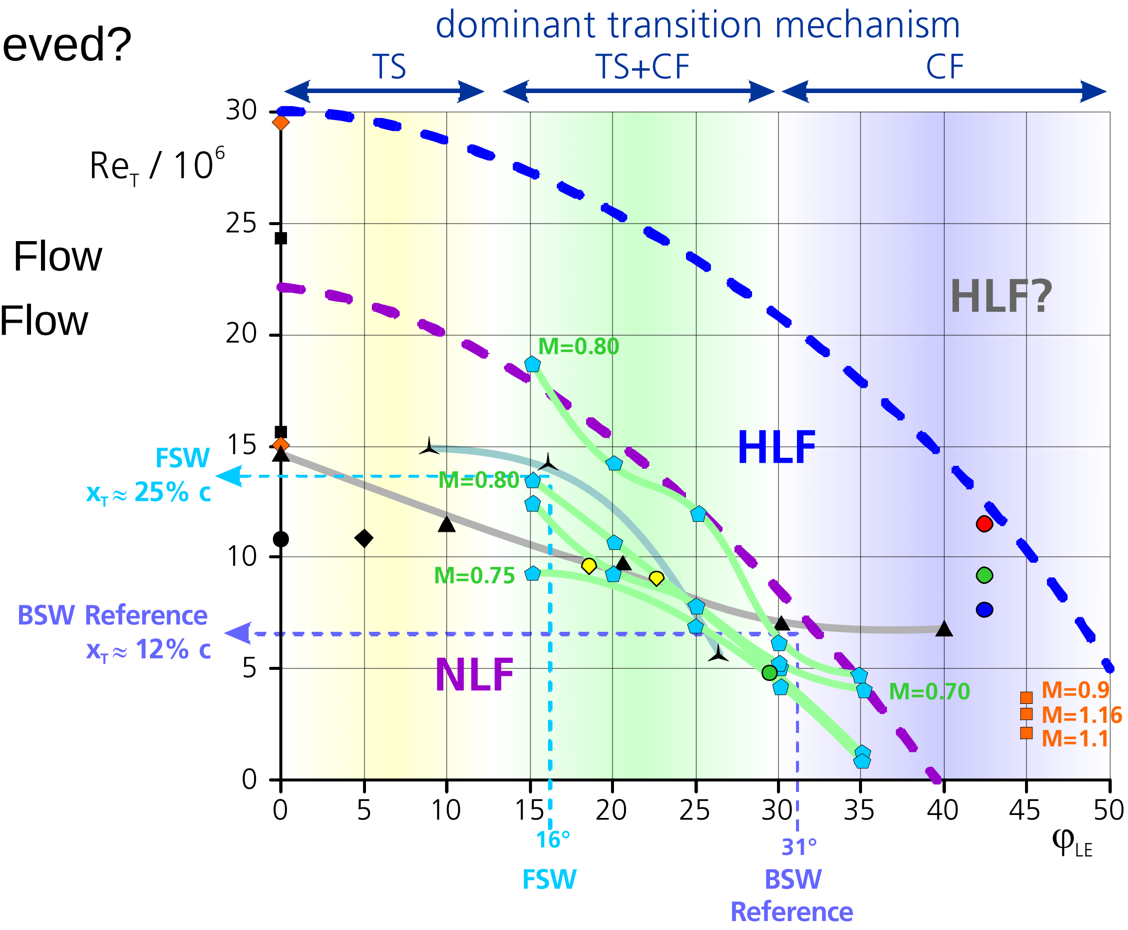
- FSW
- φ_{LE} is smaller than $\varphi_{50\%}$



Laminar Flow Limits for Swept Wings

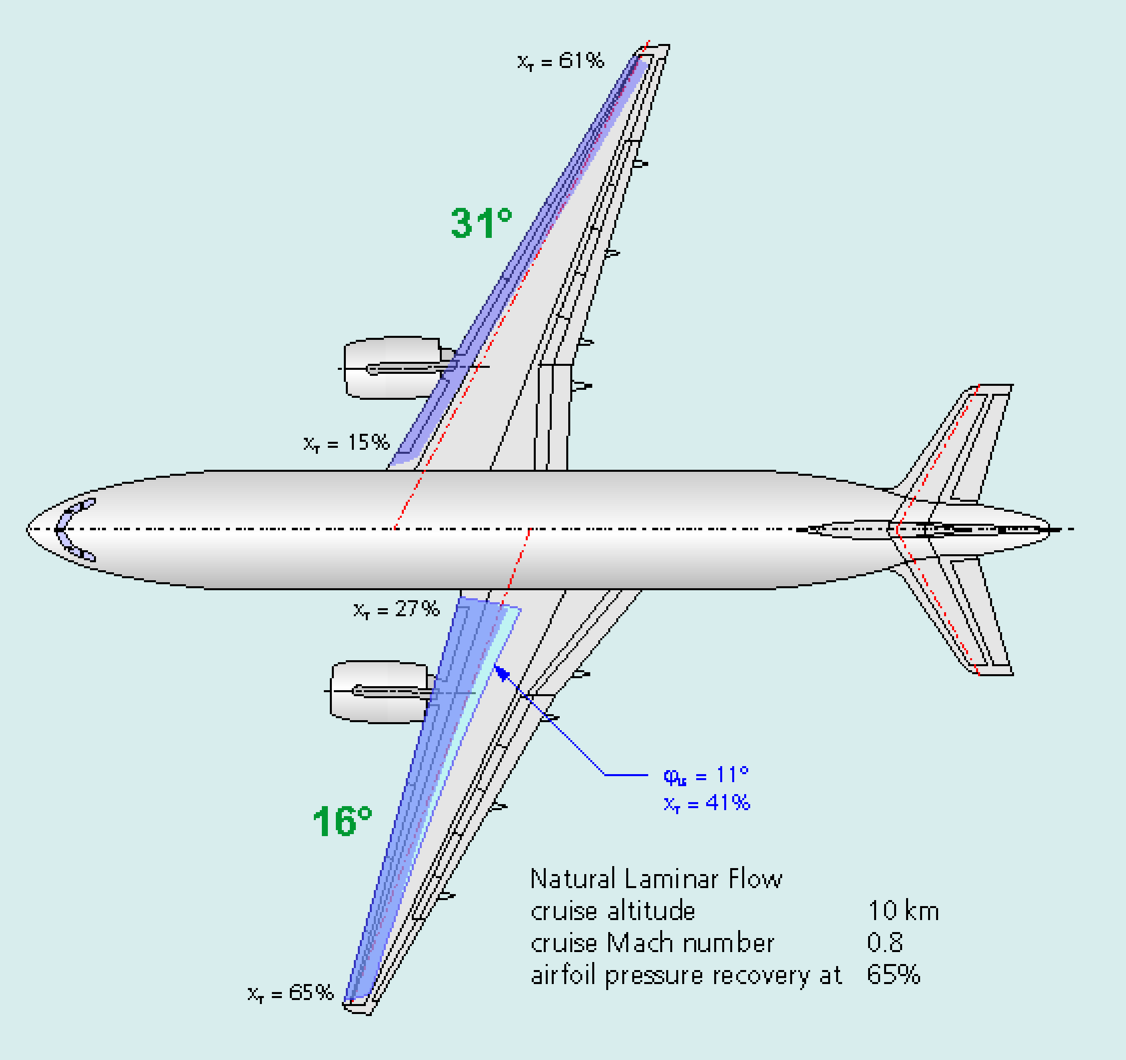
- What has been achieved?

- Regimes of
  - Natural Laminar Flow
  - Hybrid Laminar Flow



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°.

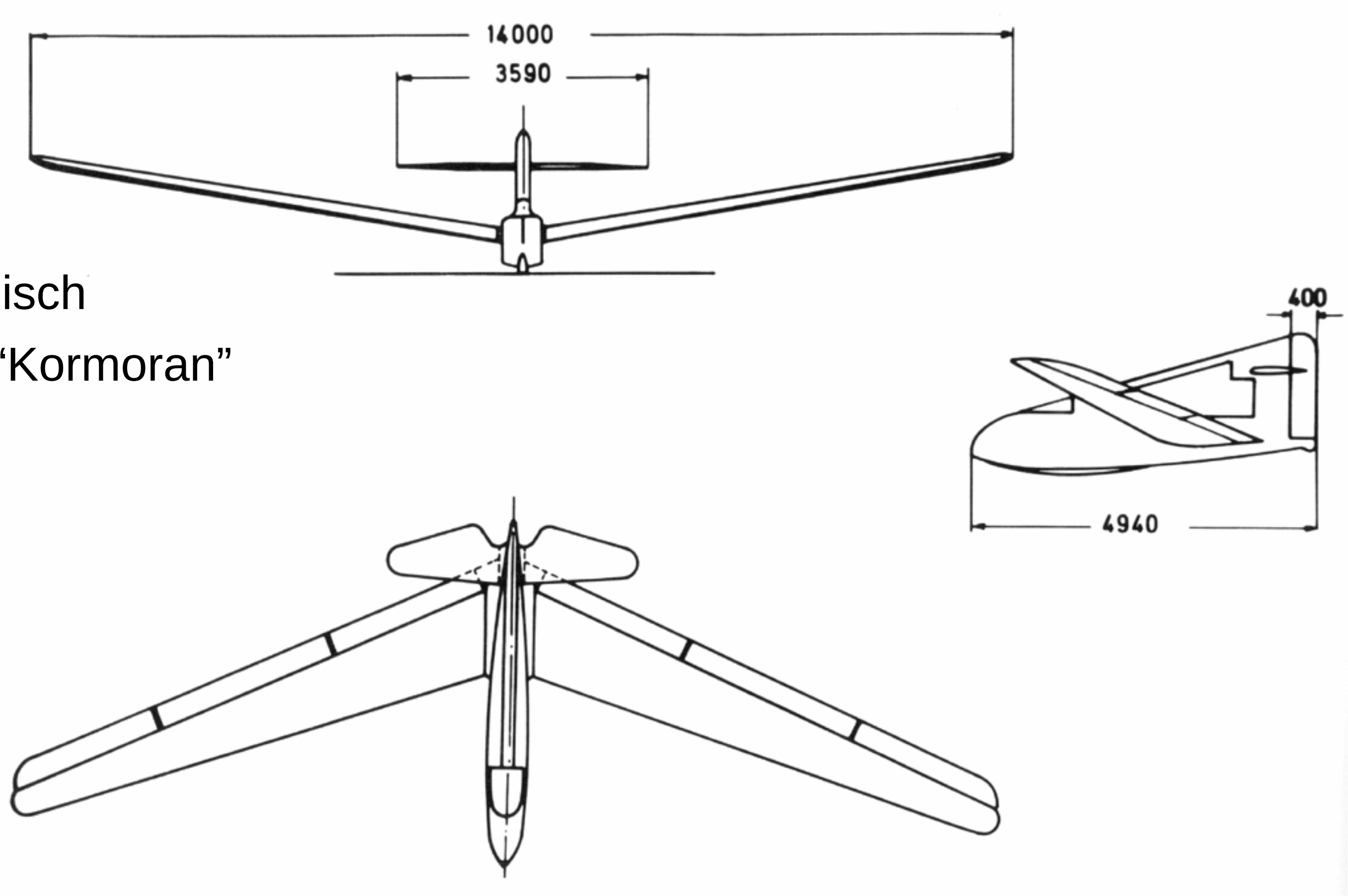


Natural Laminar Flow	
cruise altitude	10 km
cruise Mach number	0.8
airfoil pressure recovery at	65%

Some historic Forward Swept Wing Designs

Alexander Lippisch

1935: DFS 42 “Kormoran”



Some Historic Forward Swept Wing Designs

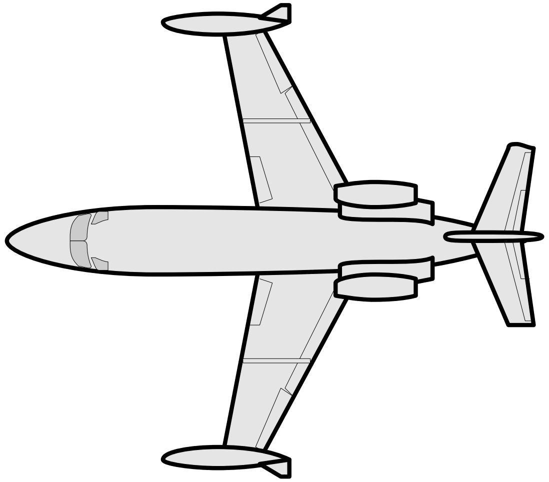
Hans Wocke

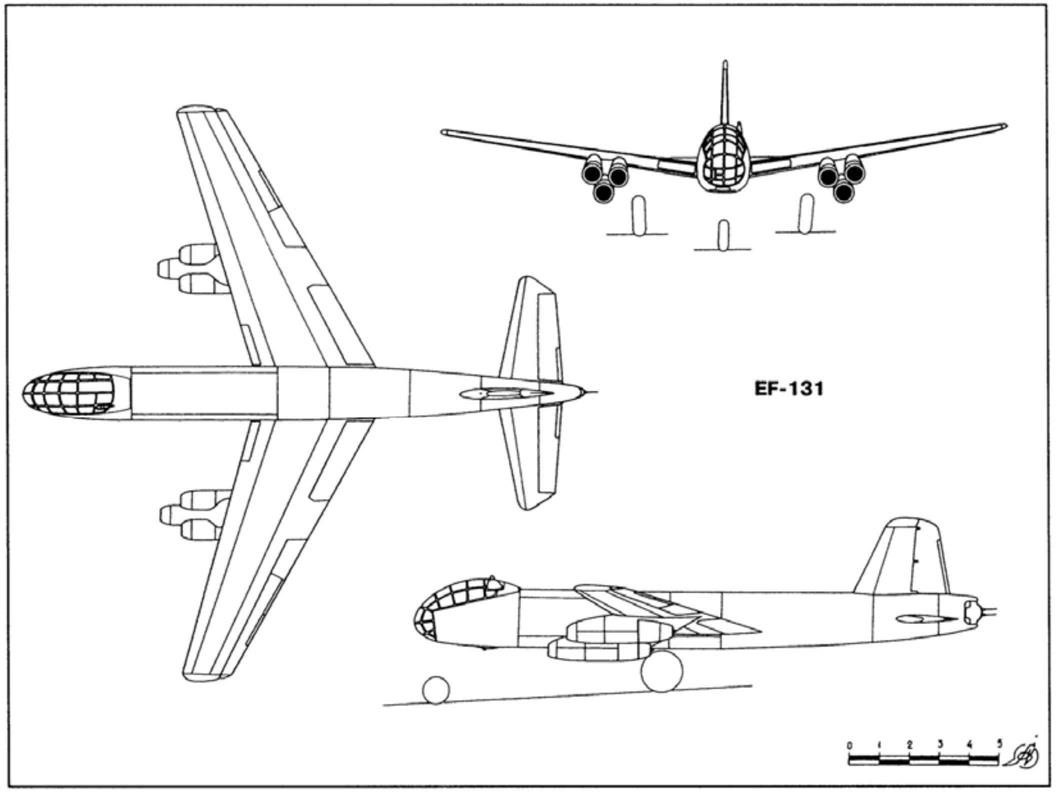
1942: Junkers 287

1946: EF 131, 140 (Russia)

1970: HFB 320 “Hansa Jet”

(over 50 built)





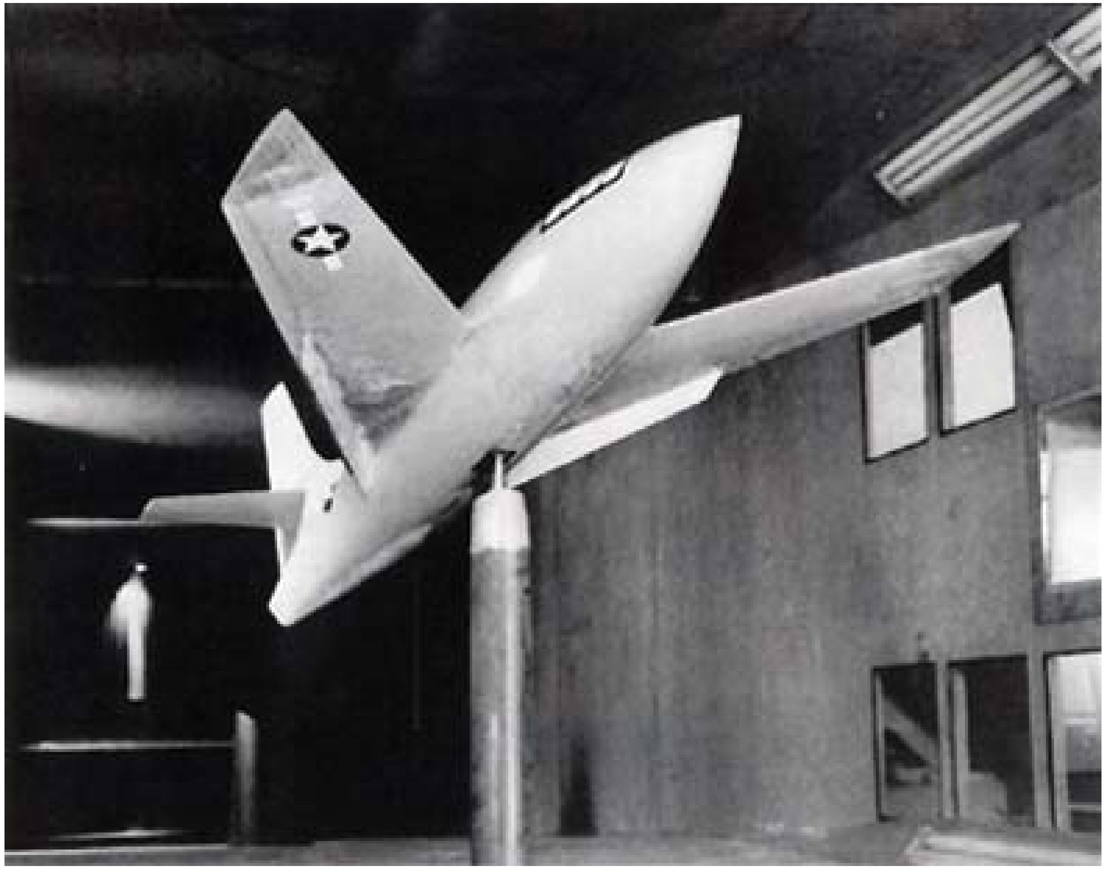
Dreiseitenzeichnung der EF 131

Some Historic Forward Swept Wing Designs

Bell

1945: X-1

(test configuration)



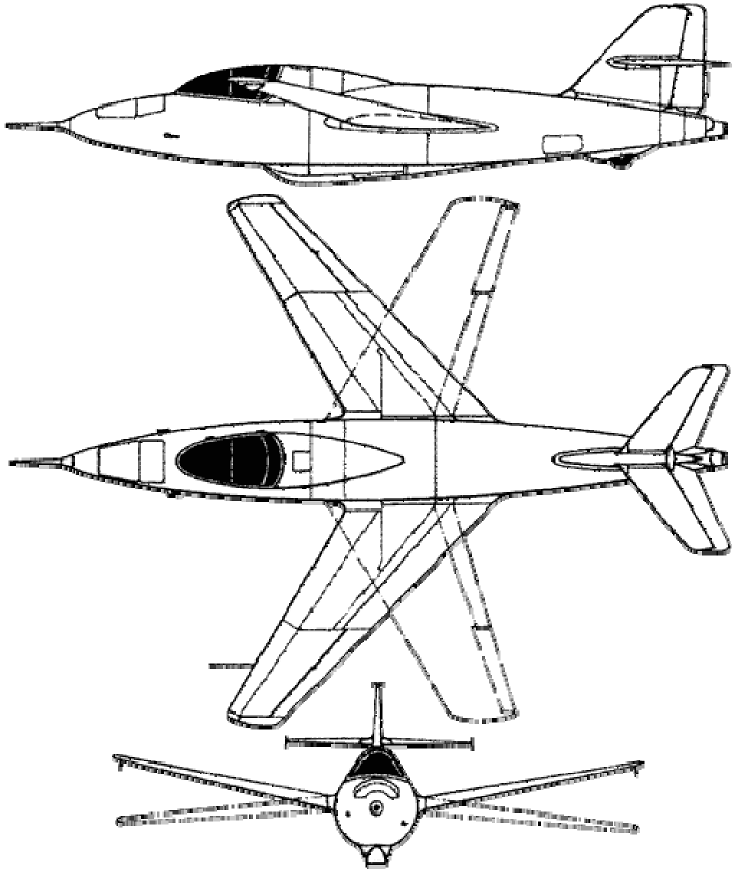
Some Historic Forward Swept Wing Designs

W. P. Tsybin

1947: LL-3

Experimentalmaschine von W. P. Zybin

"Die Luftfahrt der UdSSR 1917-1977", K.-H. Eyermann, p. 135



Some Historic Forward Swept Wing Designs

Grumman

1985: X-29

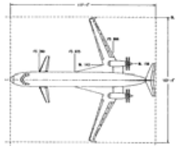
2000: Suchoi S-37

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC85-33297-23 Date: 1985 Photo by: NASA

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.

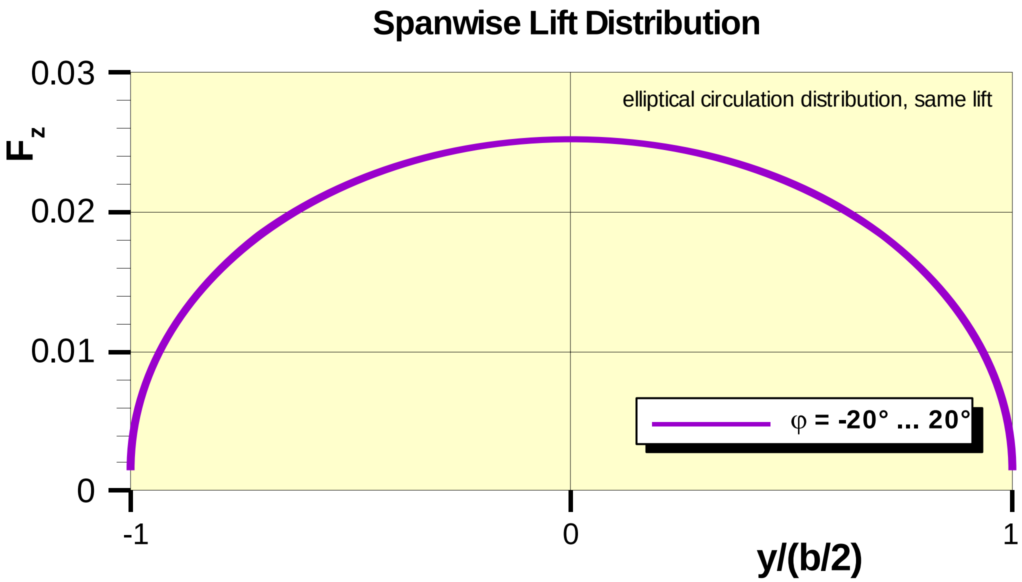




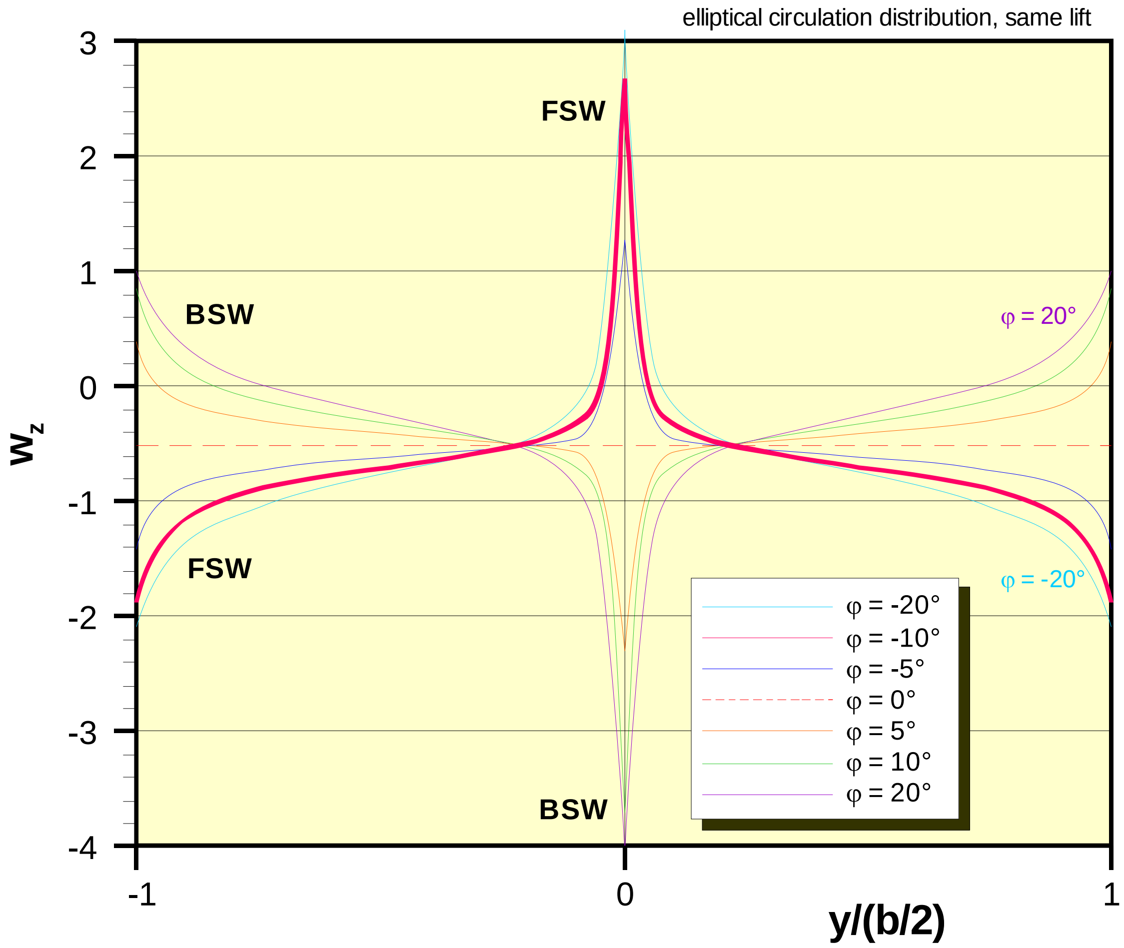

Flow Field of Swept Wings

- 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

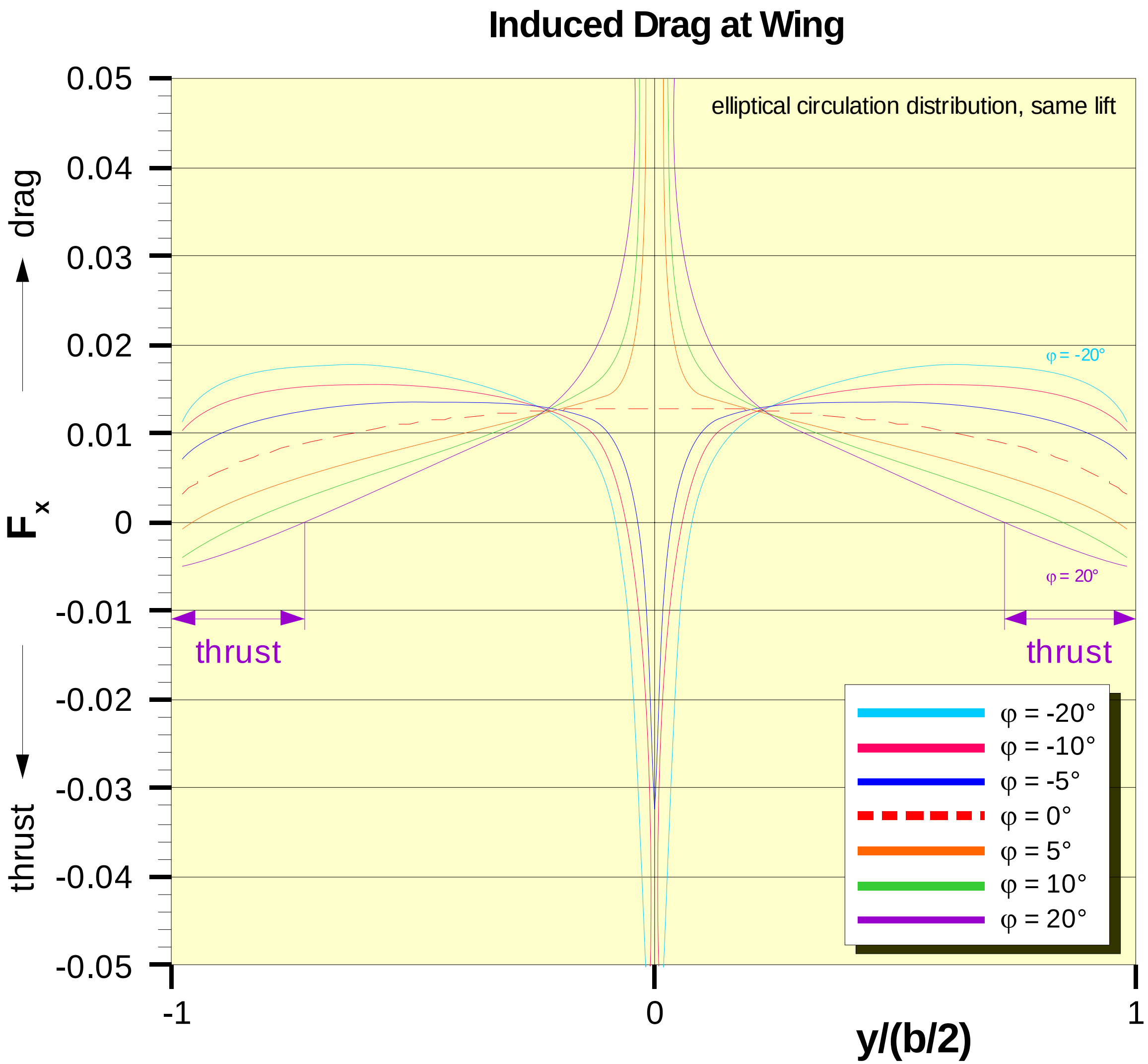
- All wings have the same mean downwash velocity.
- Sweep affects the spanwise downwash distribution.



Downwash Velocity at Wing

Flow Field of Swept Wings

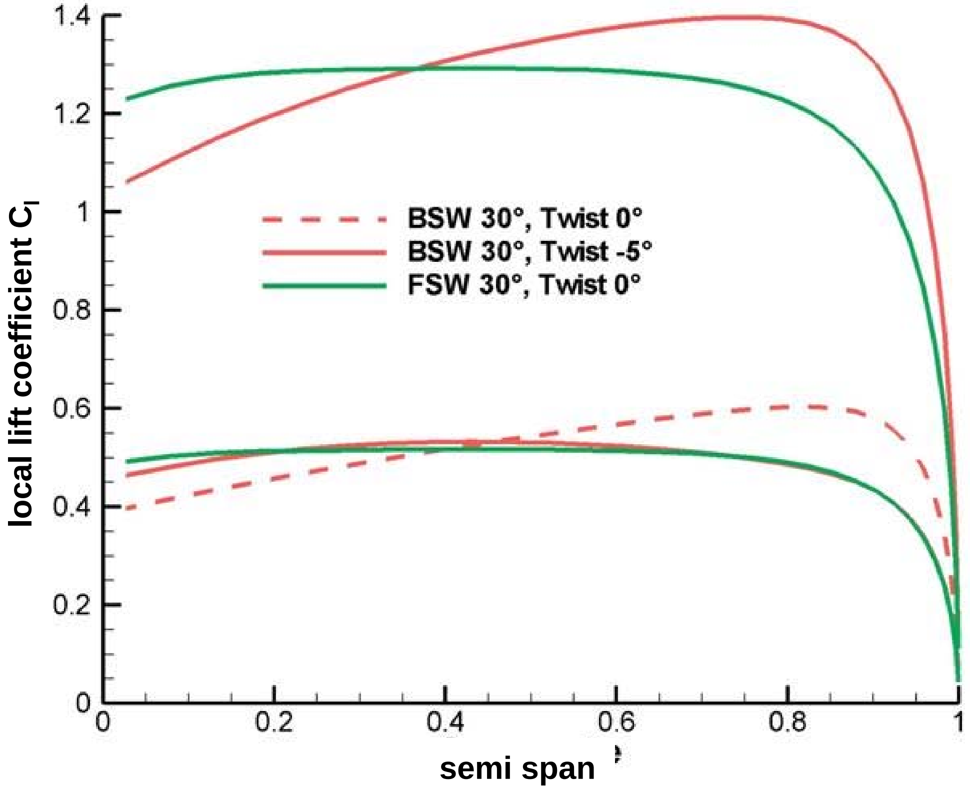
- All wings have the same induced drag.
- Sweep affects the spanwise drag distribution.
- BSW has thrust at tips.
- FSW has thrust at root.



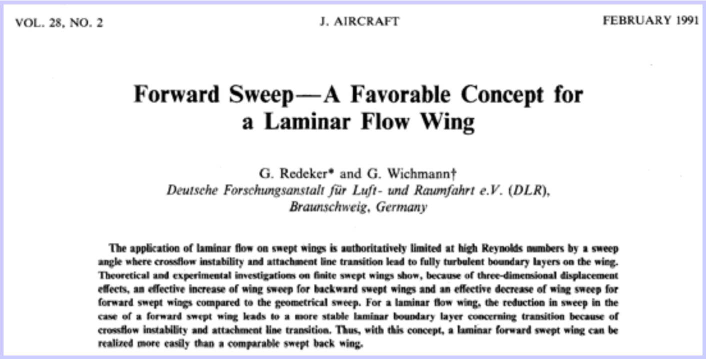
Aerodynamics of Tapered Swept Wings

- 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



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Forward Sweep—A Favorable Concept for a Laminar Flow Wing

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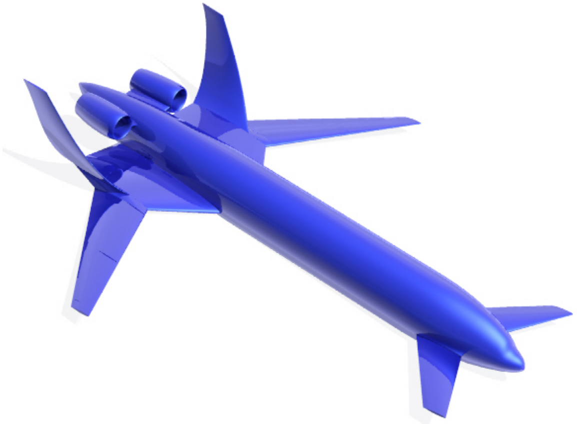
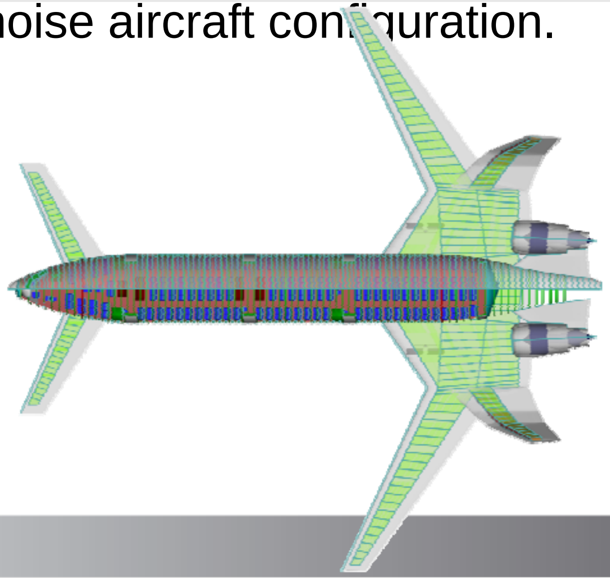
Braunschweig, Germany

The application of laminar flow on swept wings is authoritatively limited at high Reynolds numbers by a sweep angle where crossflow instability and attachment line transition lead to fully turbulent boundary layers on the wing. Theoretical and experimental investigations on finite swept wings show, because of three-dimensional displacement effects, an effective increase of wing sweep for backward swept wings and an effective decrease of wing sweep for forward swept wings compared to the geometrical sweep. For a laminar flow wing, the reduction in sweep in the case of a forward swept wing leads to a more stable laminar boundary layer concerning transition because of crossflow instability and attachment line transition. Thus, with this concept, a laminar forward swept wing can be realized more easily than a comparable swept back wing.

- 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, <u>turbulent wing</u>
    - Design of a forward swept, <u>laminar wing</u>
    - Application of FSW to low noise aircraft configuration.

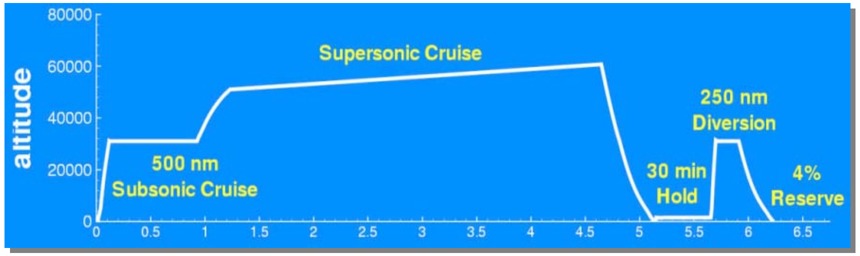


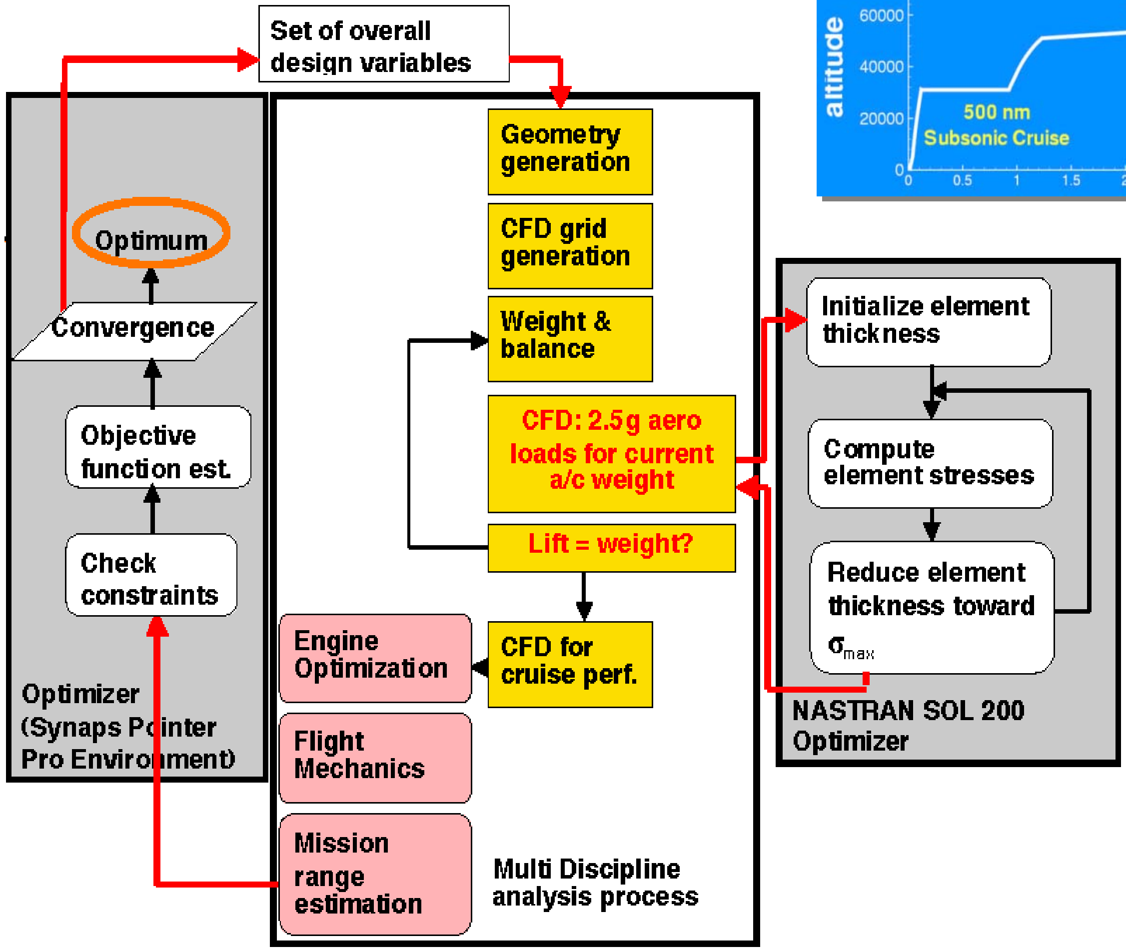


Multidisciplinary Optimization of Forward Swept Wings

Graphics courtesy Ulrich Herrmann.

- CISAP Project





Set of overall design variables

Optimum

Convergence

Objective function est.

Check constraints

Optimizer (Synaps Pointer Pro Environment)

Geometry generation

CFD grid generation

Weight & balance

CFD: 2.5g aero loads for current a/c weight

Lift = weight?

CFD for cruise perf.

Engine Optimization

Flight Mechanics

Mission range estimation

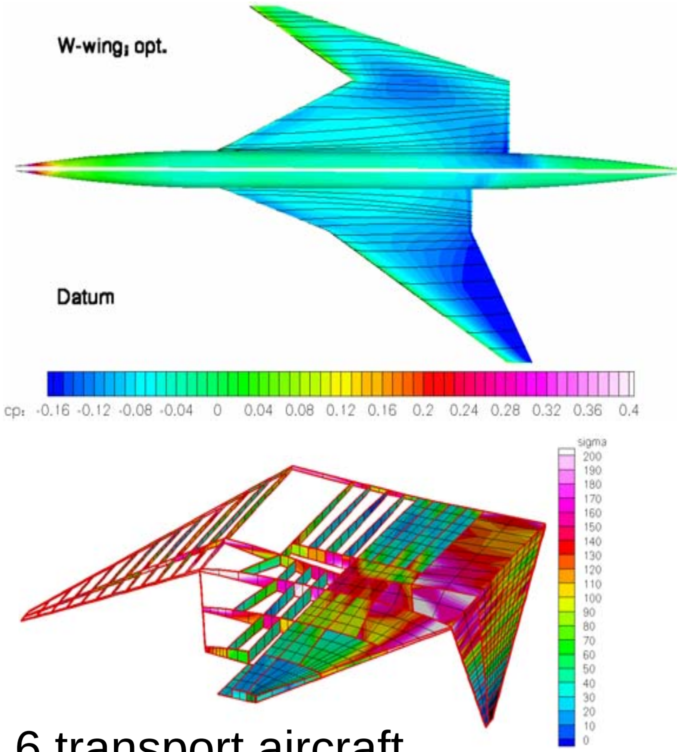
Multi Discipline analysis process

Initialize element thickness

Compute element stresses

Reduce element thickness toward σ_{max}

NASTRAN SOL 200 Optimizer



- MDO-Optimization of M=1.6 transport aircraft.

Design of Forward Swept Wings

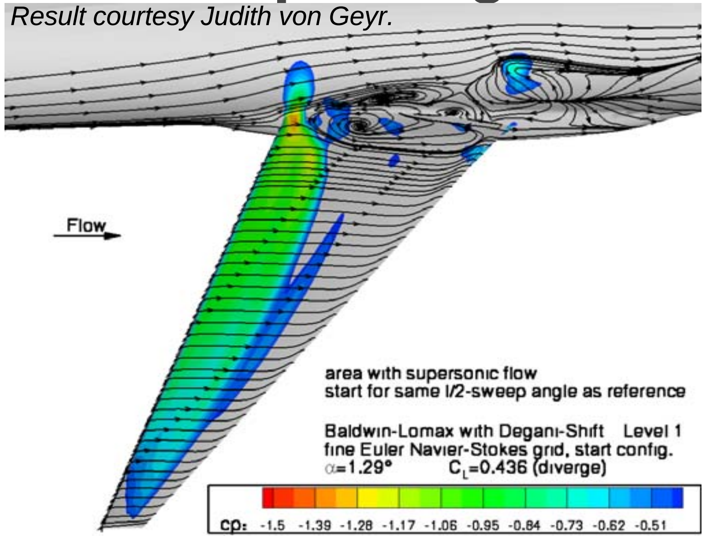
- Mono-Disciplinary Design & Optimization procedure applied at DLR in national project (LuFo/K2020):
  - Selection of planform (e.g. based on preliminary design).
  - Definition of a matching wing body configuration.
  - Selection of suitable basic airfoil sections.
  - Application of Navier-Stokes solver.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

- No structural constraints applied → approx. elliptical lift distribution.

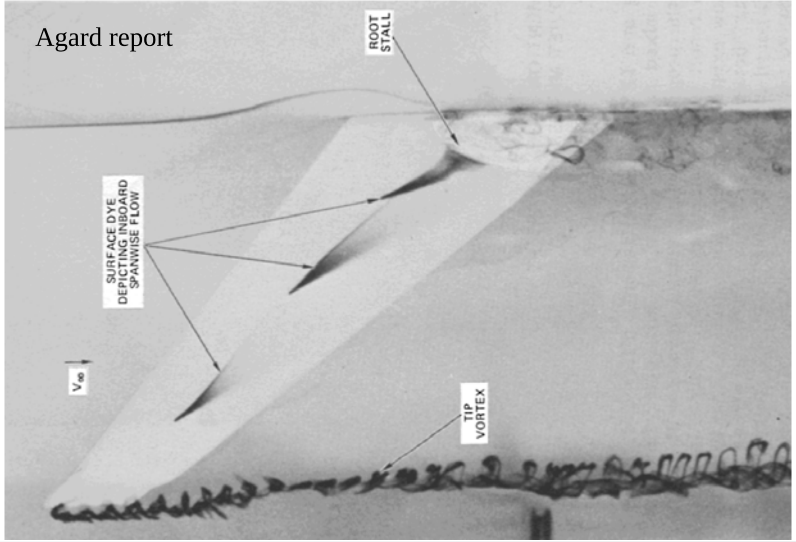
Design and Integration of Forward Swept Wings

- 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.



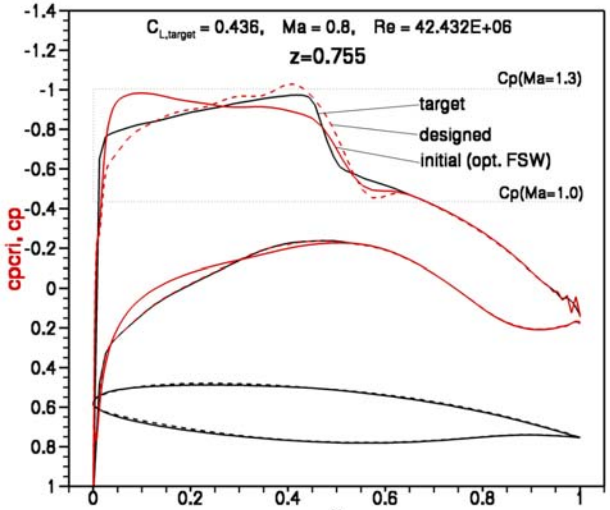
Result courtesy Judith von Geyr.



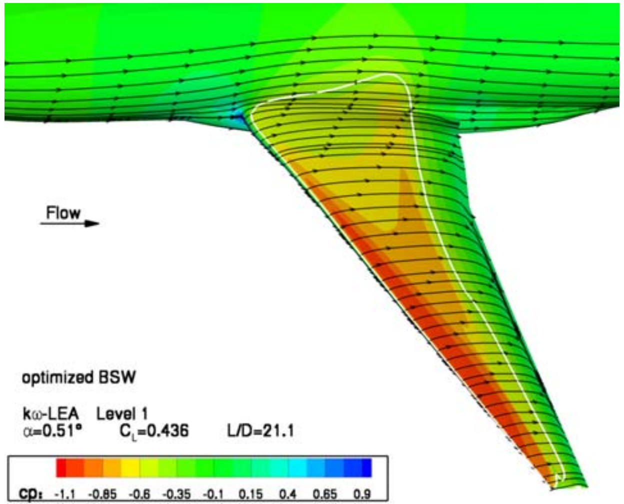
Agard report

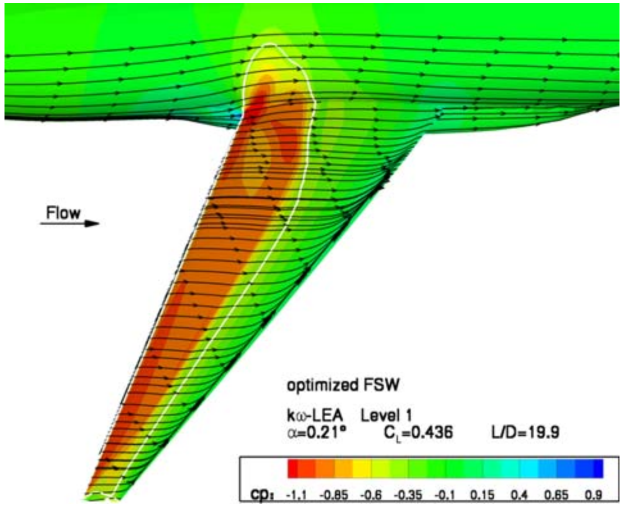
Design and Integration of Forward Swept Wings

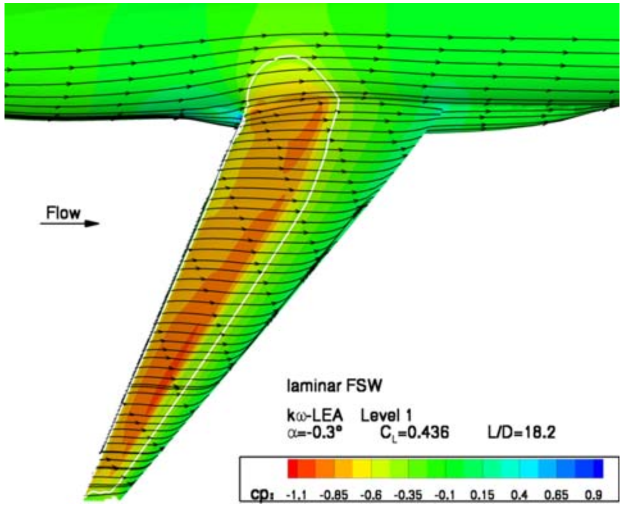
- Optimization of a BSW reference wing:
  - $M = 0.8$, $\varphi_{0\%} = 31°$, $\varphi_{50\%} = 24°$.
- Optimization of a FSW reference wing :
  - $M = 0.8$, $\varphi_{0\%} = 16°$, $\varphi_{50\%} = 24°$.
- L/D of both turbulent wings favor FSW:
  - $L/D_{\text{wing, BSW}} = 26.0$ $L/D_{\text{wing, FSW}} = 27.5$.



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.

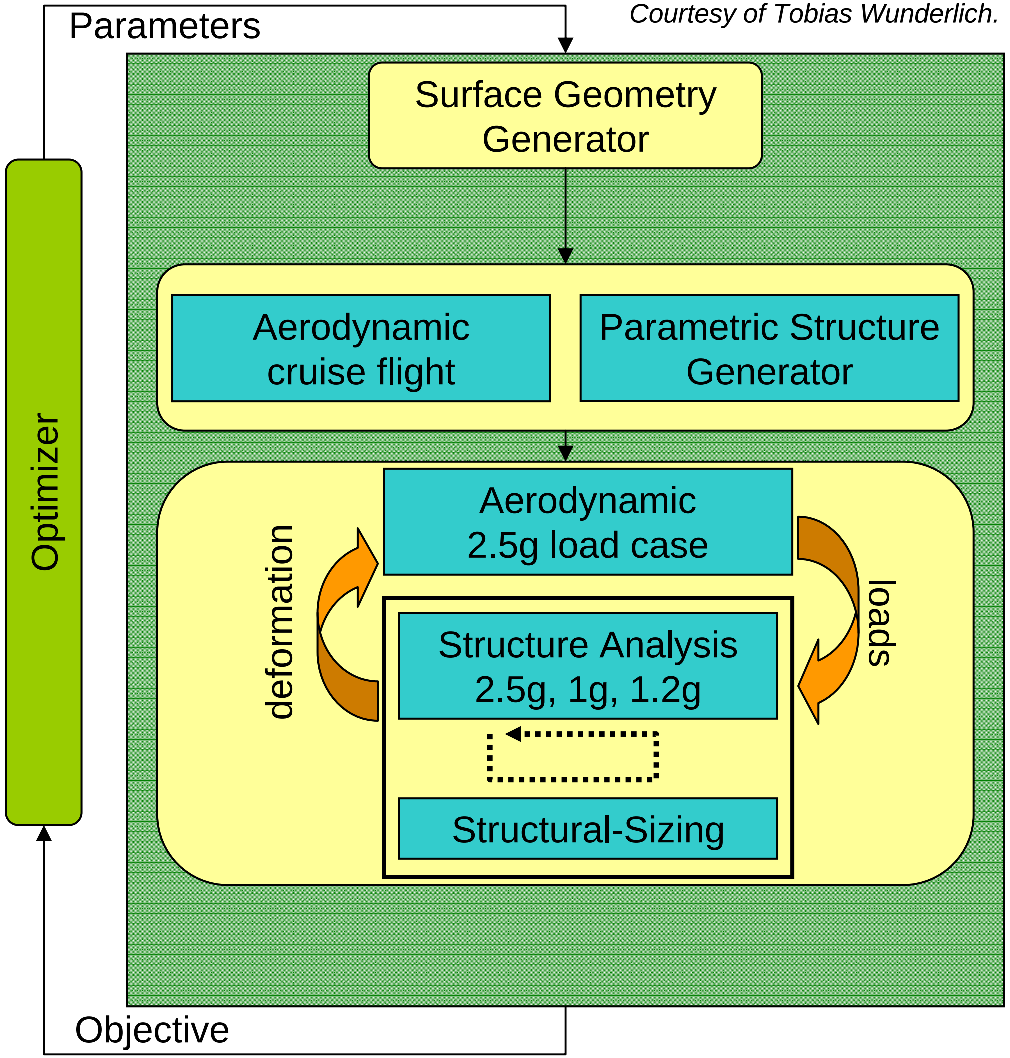
- Use high fidelity methods for accurate modeling:
  - aerodynamics:
    - model transonic effects (Euler, Navier-Stokes),
    - model transition (TS and CF stability analysis, ALT criterion?),
    - suction distribution (for HLF design).
  - structures:
    - finite element models,
    - structural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

Courtesy of Tobias Wunderlich.

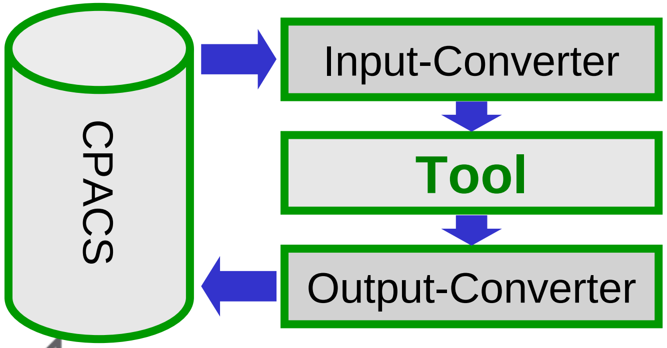


Multi Disciplinary Optimization Process

- 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.

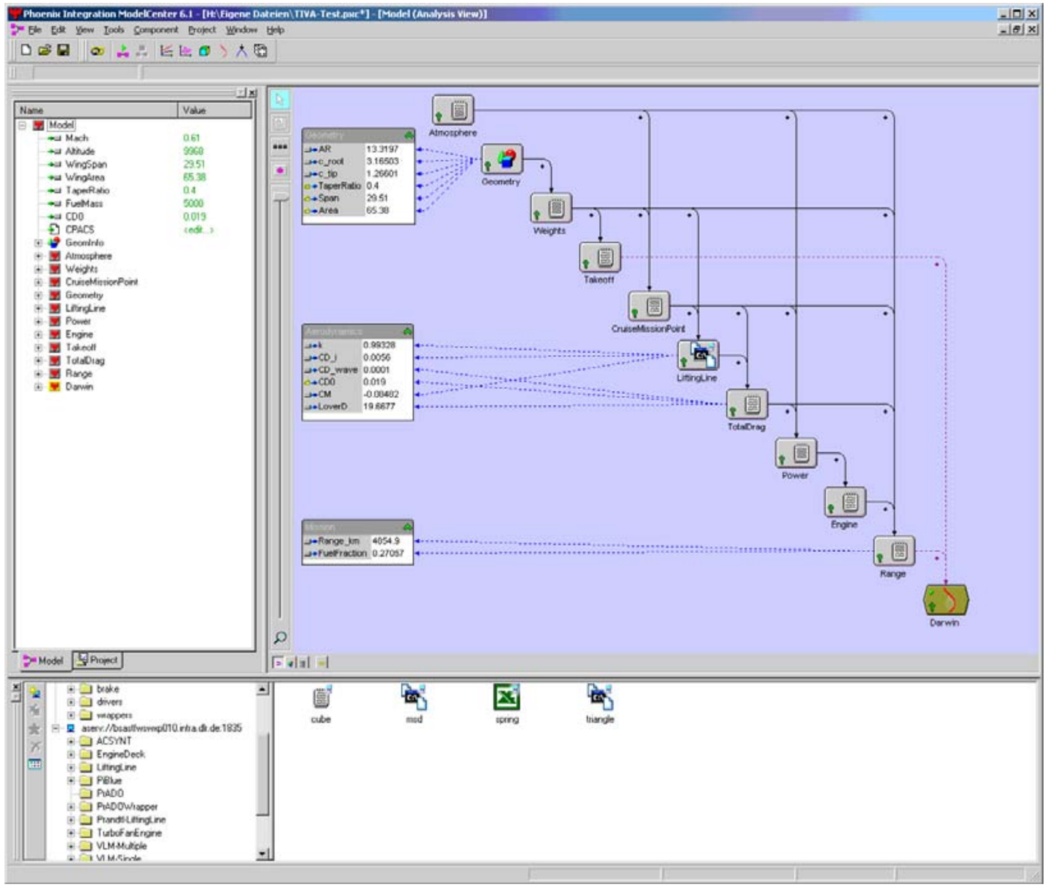


CPACS

Input-Converter

Tool

Output-Converter



Phoenix Integration ModelCenter 6.1 - [H:\Eigene Dateien\TIVA-Test.pac*] - [Model (Analysis View)]

Name	Value
Model	
Mach	0.61
Altitude	9960
WingSpan	29.51
WingArea	65.38
TaperRatio	0.4
FuelMass	5000
CD0	0.019
CPACS	<edit...>
GeomInfo	
Atmosphere	
Weights	
CruiseMissionPoint	
Geometry	
LiftingLine	
Power	
Engine	
Takeoff	
TotalDrag	
Range	
Darwin	

Geometry

AR	13.3197
c_root	3.16503
c_tip	1.26601
TaperRatio	0.4
Span	29.51
Area	65.38

Aerodynamics

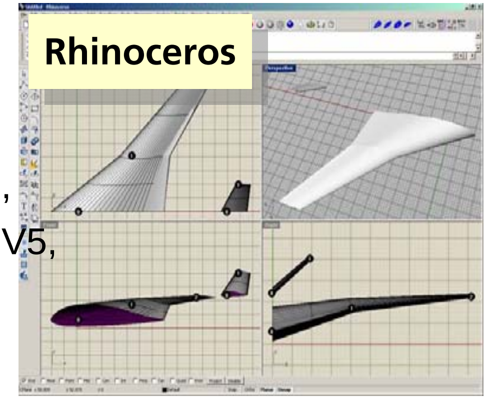
k	0.99328
CD_i	0.0056
CD_wave	0.0001
CD0	0.019
CM	-0.00402
LoverD	19.6677

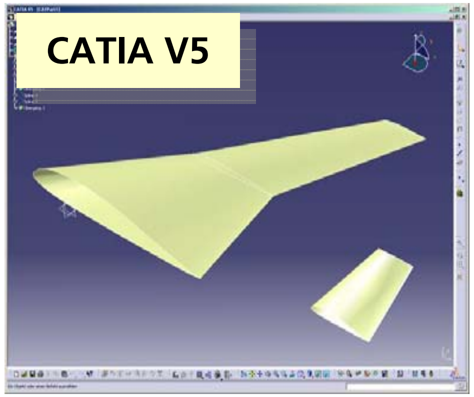
Mission

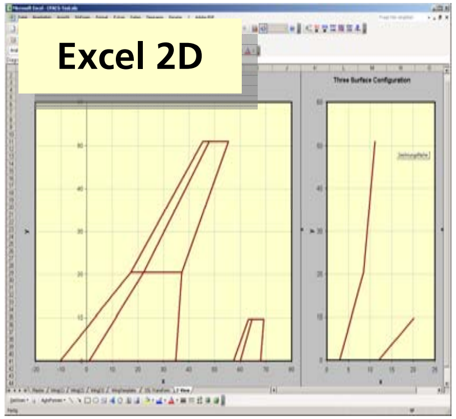
Range_km	4054.9
FuelFraction	0.27057

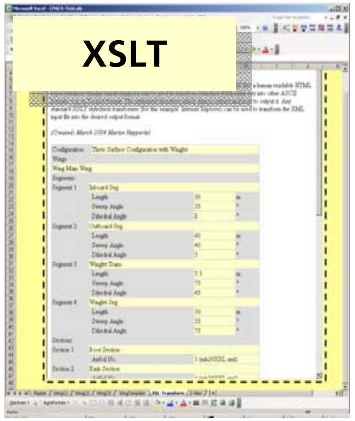
Multi Disciplinary Optimization Process

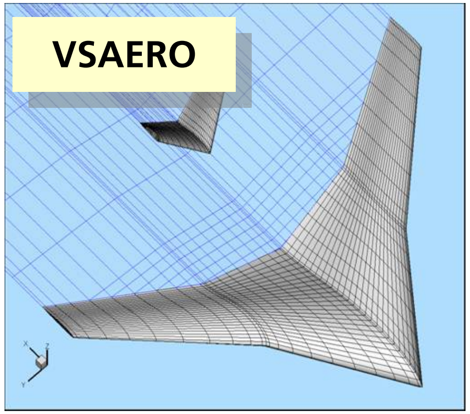
- Single aircraft description „CPACS“
- Simple example: wing geometry
- Automatic generation of:
  - Lists and reports (XSLT),
  - simple 2D-views,
  - simple CAD model Rhinoceros,
  - parametric CAD model CATIA V5,
  - aero method VSAERO,
  - … up to Hi-Fi methods.

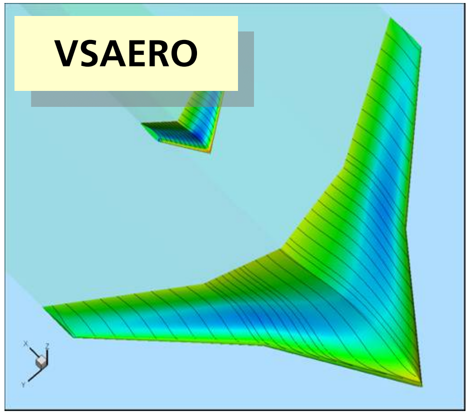

Rhinoceros


CATIA V5


Excel 2D


XSLT


VSAERO


VSAERO

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 (→ CO_2, NO_x, 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...

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AD-1