High-Lift Aerodynamics
another 100 years anniversary

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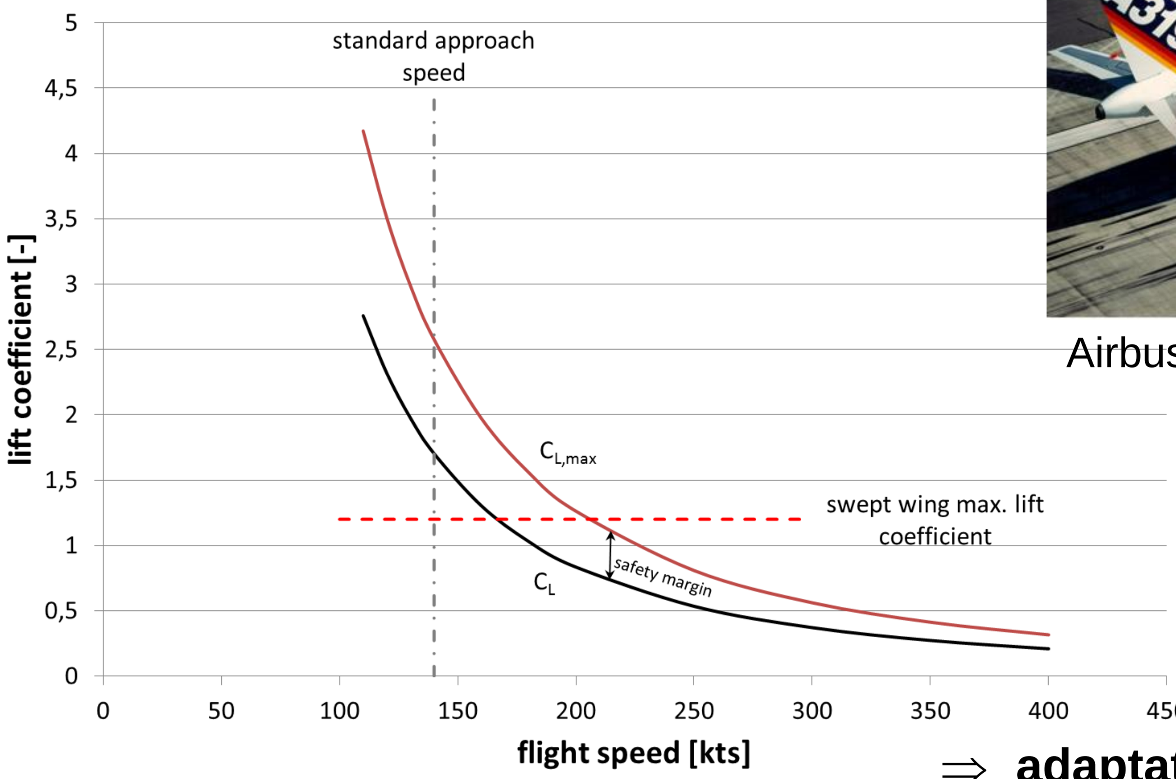
Bucharest, Romania

DLR

High-Lift Systems
Why high-lift wings?

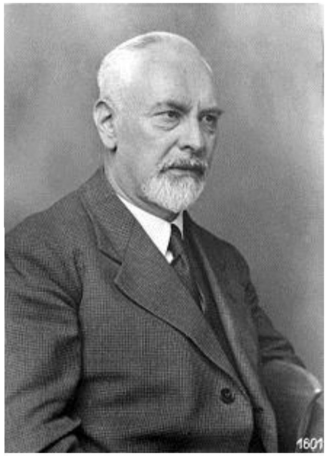


Airbus A319 at touch-down

example: typical single-aisle aircraft

$\Rightarrow$ **adaptation of the wing for flight conditions at take-off / landing**

The early beginnings
boundary layer control



Ludwig Prandtl
(1875-1953)

- publishes „Über Flüssigkeitsbewegung bei sehr kleiner Reibung“ in 1904
- foundation of boundary layer theory
- describes first time the importance of boundary layer development for flow separation
- proposes suction for stabilization of boundary layer
- consequently, in the following separation prevention is regarded as boundary layer control

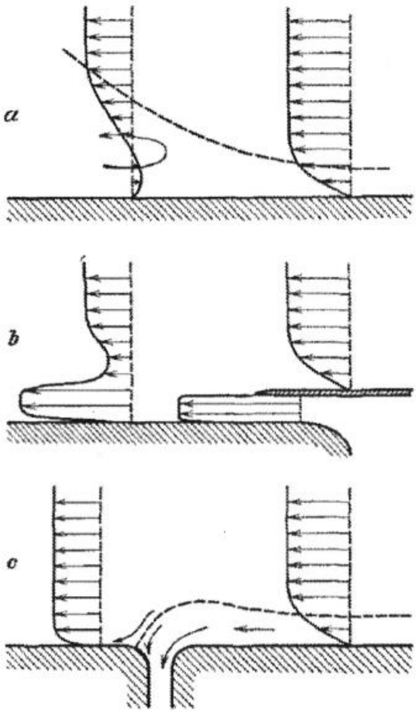


Fig. 5. (Schematisch, Grenzschichtdicken überhöht gezeichnet.) Entwicklung einer Grenzschicht in einem Gebiet mit kräftigem Druckanstieg längs der Körperoberfläche,
a) ohne besondere Vorkehrungen (Ablösung),
b) Verhinderung der Ablösung durch Blaswirkung,
c) Verhinderung der Ablösung durch Absaugung.

Quelle: Springer

The early beginnings
camber and area increase

J.L. Nayler, E.W. Stedman und W.J. Stern

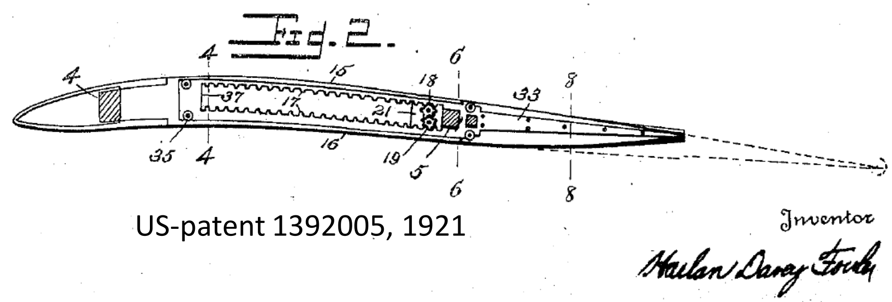
- experiment 1912-1914 on airfoils with hinged trailing edges
- today‘s principle of rudders and control surfaces

Fig. 2 RAF 9 airfoil with a 0.385c plain flap tested in 1912-1913.

Harlan Davey Fowler

(1895-1982)

- patents 1921 a wing with variable wing area (no slot)



US-patent 1392005, 1921

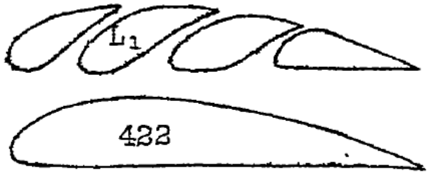
Quellen: Cranfield University, A.M.O Smith, EPA

The Invention of the Slotted Airfoil

Gustav Lachmann (1896-1966)

The (theoretical) invention

- investigated means of preventing stall after an own accident with a stalling aircraft, in 1917
- filed a patent on slotted wings in 1918 based on theoretical work
- patent is refused as the authority is not convinced that more lift can be generated by cutting the wing into pieces

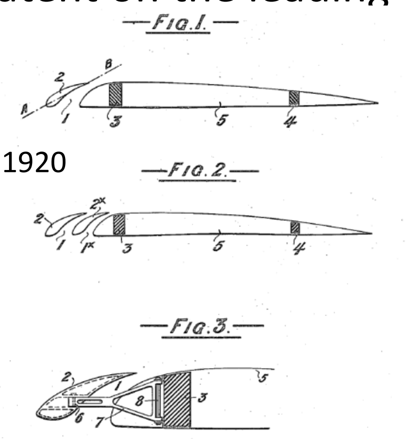


Sources: AGARD CP 515, NACA, FlightGlobal

The Invention of the Slotted Airfoil

The (experimental) invention

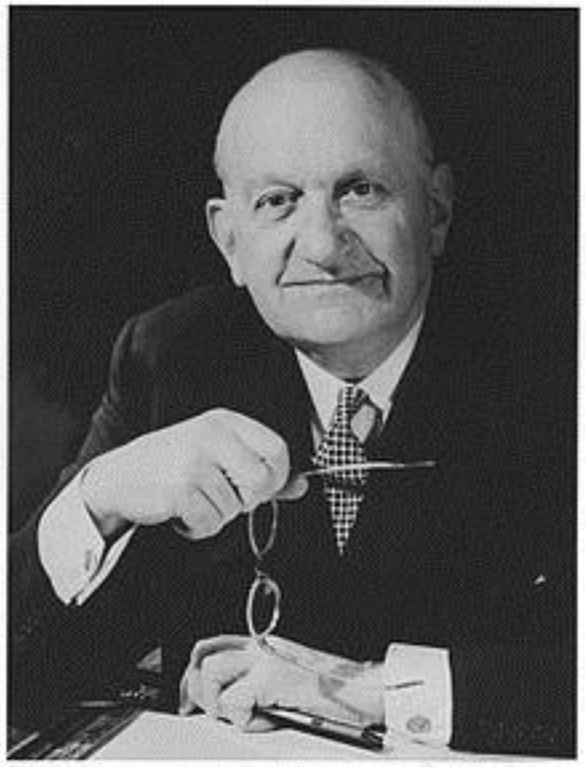
- researches strictly secret experimentally on slotted airfoils 1916-18
- recieves the patent on the leading edge slot in 1920



US-patent 135366A, 1920

- license fees on the „slat“ get biggest source of income, even more then selling planes

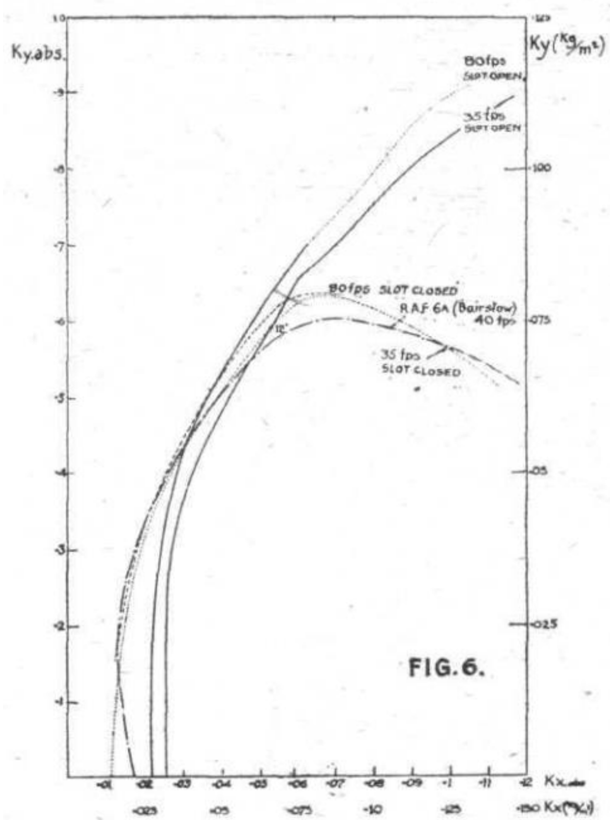
Frederick Handley Page (1885-1962)



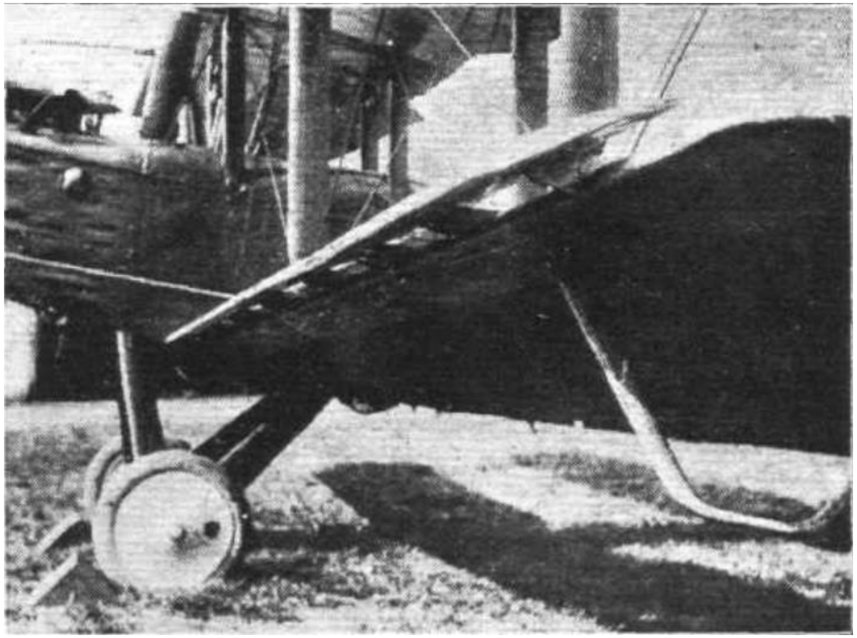
Sources: AGARD CP515, FlightGlobal, EPA

The Invention of the Slotted Airfoil

The demonstration (1921)



first full-scale experiment with Handley Page slotted wing on a D.H.9 aircraft



source: FlightGlobal

the most famous aircraft with slotted wing

Fieseler Fi-156 „Storch“

- Exterme low speed aircraft, intentionally for surveillance
- Permanently slotted wing
- Used for wiring of phone cables
- Stall speed:
  45km/h (12.5 m/s)

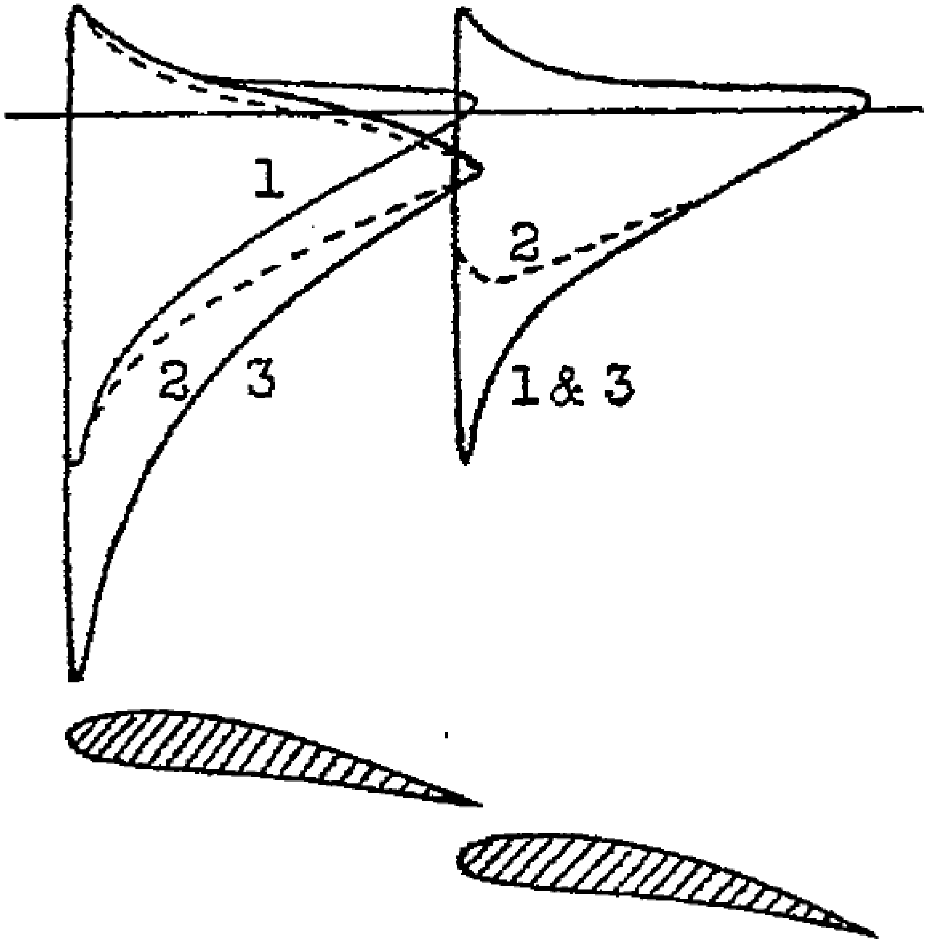
- From June 1943 until 1946, 74 license aircraft were built in Romania (ICAR factory in Bucharest)

Gauli-Clacier rescue, Nov. 1946

Image source: wikipedia

The early „understanding“

Slotted airfoil flow effects



Alfred Betz
(1885-1968)

sources: Betz A (1922) Theory of the Slotted Wing, NACA TN-100
Histaviation.com.

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The invention of the Fowler flap

Harlan Davey Fowler

(1895-1982)

- patented 1927 the Fowler-Klappe as combination of area increase, camber increase and slot flow
- feels definitely misunderstaood
- publishes 1936 „*The Fowler Wing Flap – The Originator's Own Description of the Theory and Uses of this Interesting Device*" – a must read

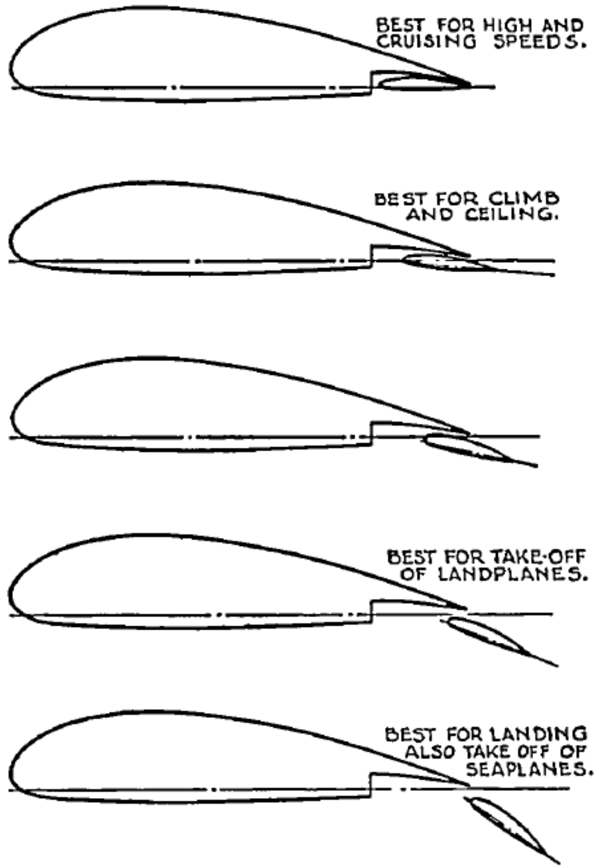


FIG. 1.—*Performance characteristics with various positions of the Fowler flap*

source: EmeraldInsight

State of knowledge 1945

Werner Krüger

Hochauftrieb – Zusammenstellung und Vergleich verschiedener Methoden und Bauarten

AVA-Bericht 43/W/38 (1943)

- comparison of all known principles of lift augmentation together with achievable maximum lift coefficients
- including active flow control by suction and blowing

A.R. Weyl

High-Lift Devices and Tailless Aeroplanes

Aircraft Engineering, October/November 1945

- detailed description principles of different high-lift devices (according state of knowledge)
- differentiation between „assisted“ and „unassisted“ methods
- everything directly considered as boundary layer control

The understanding of high-lift flows

„High-Lift Aerodynamics“
37th Wright Brothers Lecture, 1972

- Chief Aerodynamics Engineer for Research at Douglas Aircraft Company
- provides first time the full understanding of slotted airfoil flows
- names 5 effects, three of them fully explainable by potential theory
- explains that the major lift generation capability is much more than boundary layer control

Apollo Milton Olin Smith
(1911-1997)

source: AIAA

State-of-the-art

Nothing to research?

- next generation aircraft will have to respect socio-economic needs more than in the past
    - CO^2 emissions
    - airframe noise perception
    - low environmental footprint (resource awareness / recycling)
    - cost awareness for affordable air transport
- targets/road map given by e.g. FlightPath 2050

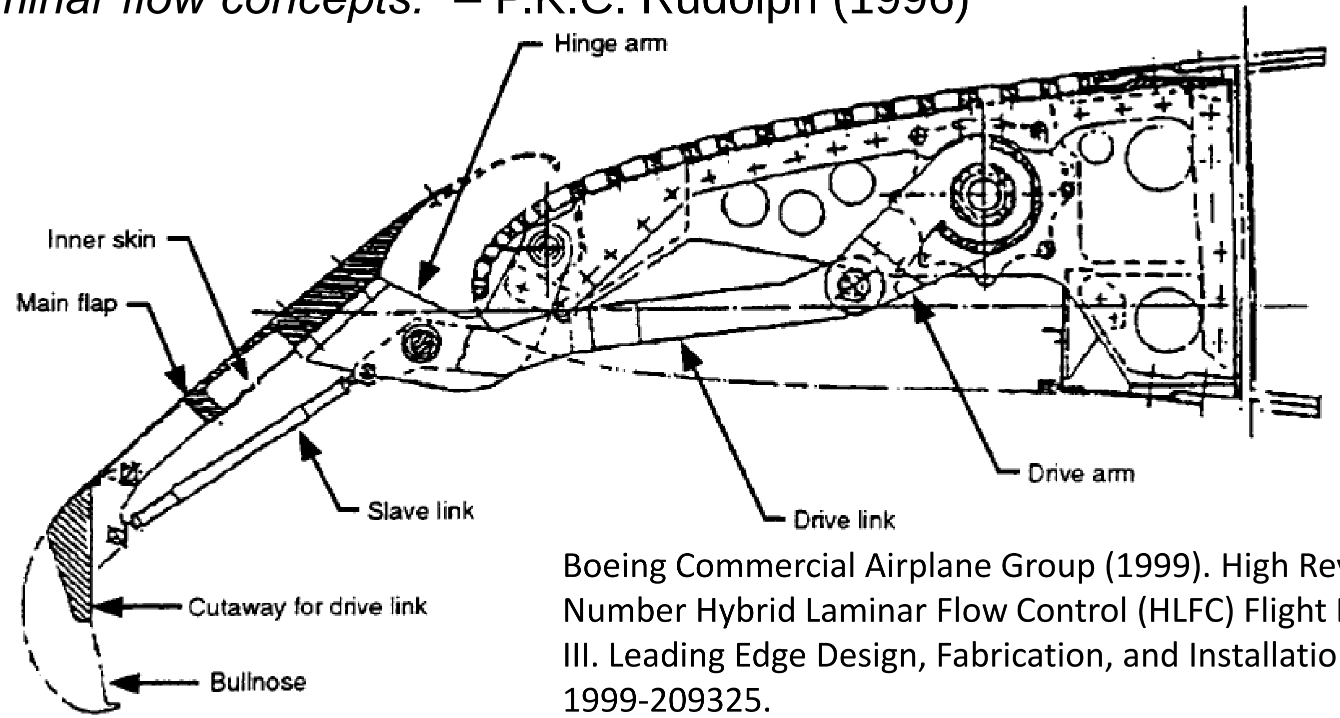
State-of-the-art

How can high-lift systems contribute?

- current high-lift system layout probably not suited to achieve new technology steps to address new challenges
    - laminar wing technology
    - airframe noise reduction (elimination of slat noise)
    - non-planar wings
    - increase in engine size
    - simplified moveable layouts (multi-functional control surfaces)
- identify suitable high-lift systems as **enabling** technologies

Krueger concept for laminar wing
Krüger Device from NASA HLFC Flight Experiment on a Boeing 757

•*“**Fixed camber Krueger** – There has been no effort to develop the fixed-camber Krueger into a device that has characteristics similar to that of a slat, except for the work done on the 757 hybrid laminar flow experiment. Therefore, this area is one in which research could help the future implementation of hybrid or natural laminar flow concepts.”* – P.K.C. Rudolph (1996)

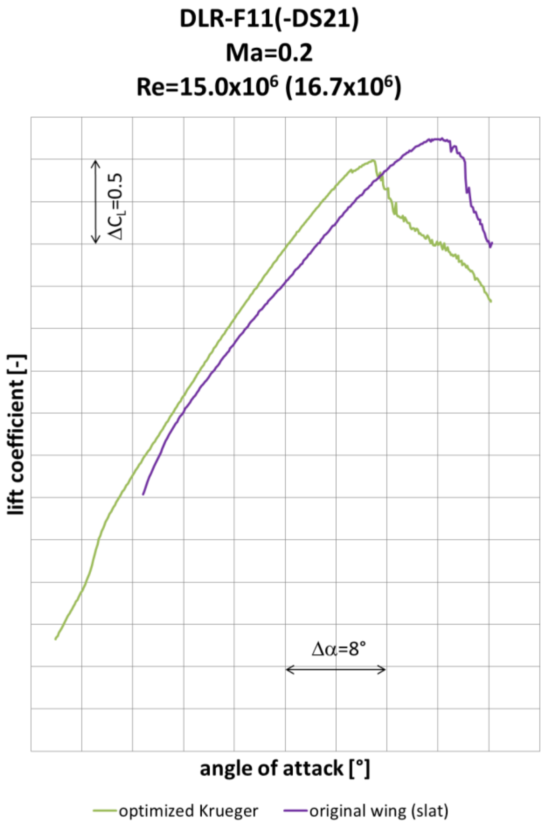


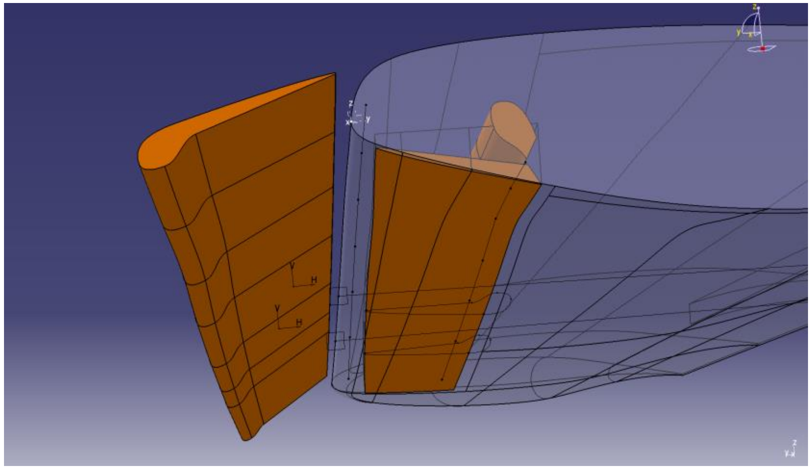
Boeing Commercial Airplane Group (1999). High Reynolds Number Hybrid Laminar Flow Control (HLFC) Flight Experiment III. Leading Edge Design, Fabrication, and Installation. NASA/CR-1999-209325.

Krueger concept for laminar wing

design new concepts for Krueger devices for laminar wings

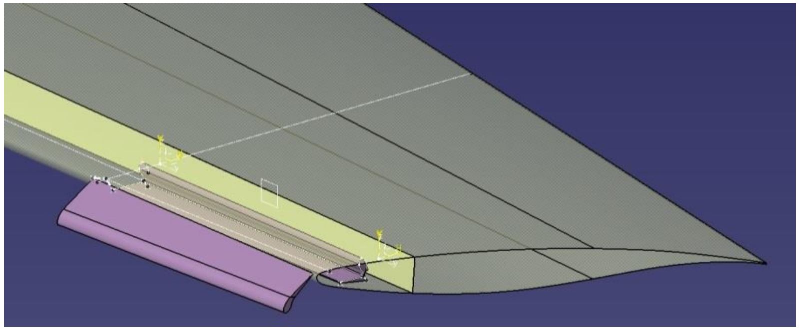
- folding bull-nose vented Krueger device
- guaranteed shielding properties
- aerodynamic performance close to slat





Krueger concept for laminar wing

AFLoNext



mature (TRL4) Krueger device concept for hybrid laminar flow control (HLFC) wings

- wing integration into HLFC leading edge

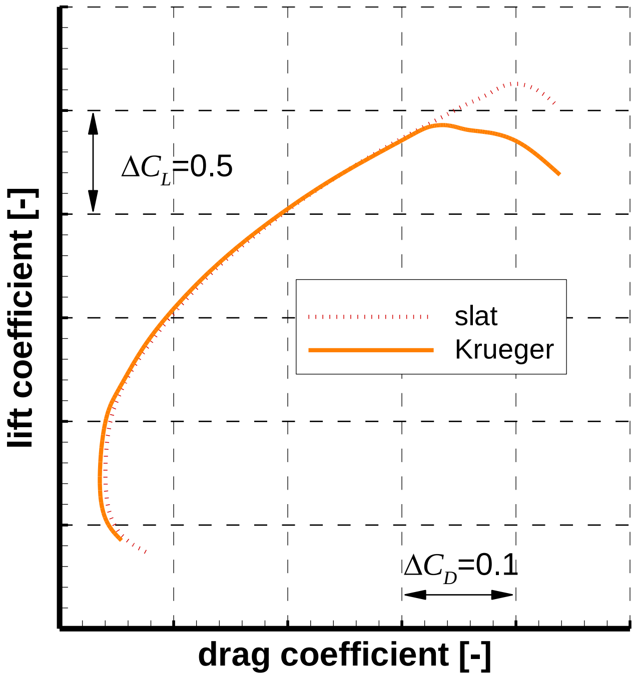
– design: DLR

– kinematics: ASCO

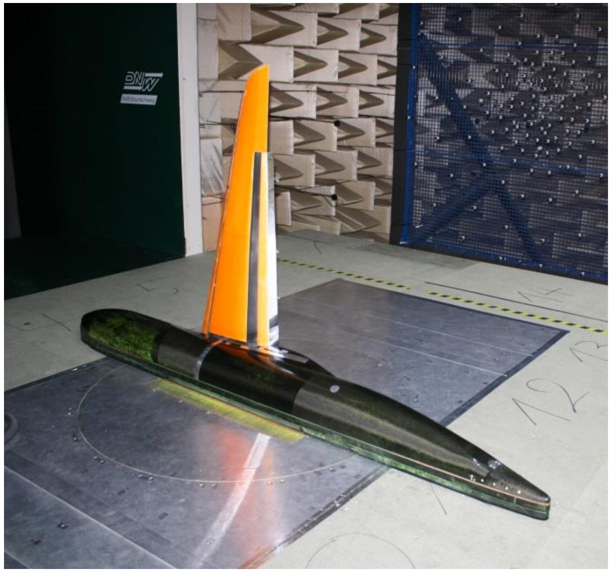
– Krueger panels: INVENT

– leading edge: INCAS

– HLFC skin: SONACA

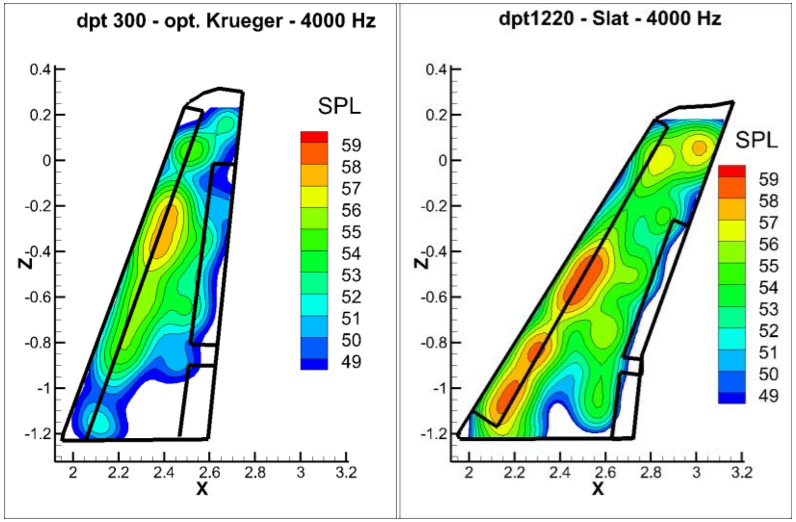


Krueger concept for laminar wing



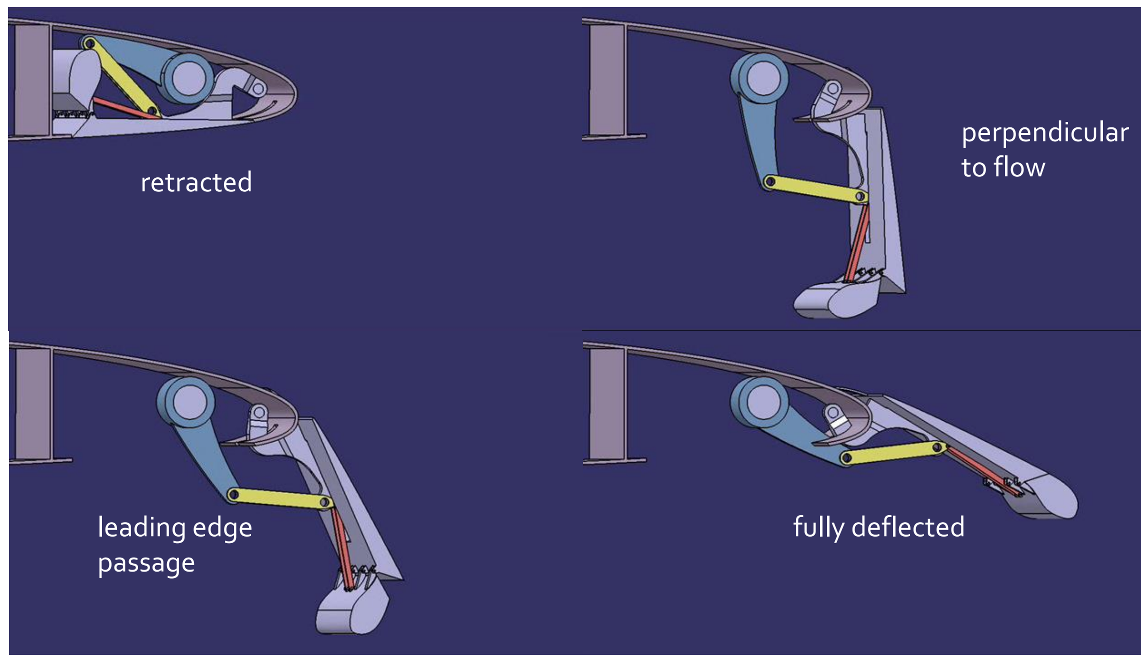
aeroacoustic assessment

- measurements in DNW-NWB
- DLR-F11 model
  - original turbulent wing with slat
  - laminar (NLF) wing with new Krueger device
  - significantly less noisy



Krueger concept for laminar wing

- deploying/retracting Krueger flap trajectory faces critical phases for handling qualities and loads
- Detailed investigations needed
- Research just started

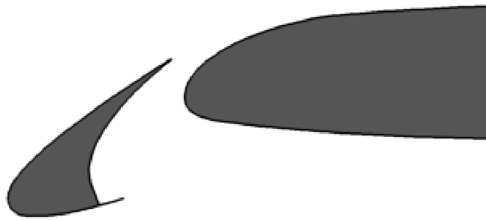


Deployment of vented folding bull-nose Krueger device

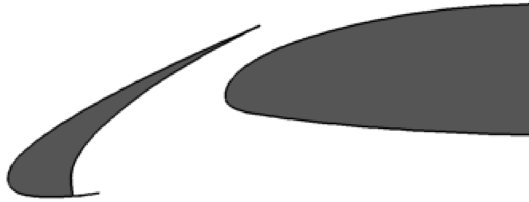
Noise Reduction at Leading Edge Devices Very Long Chord Slat (VLCS)

- low noise slat device characterized by
  - increased overlap to
    - reduce trailing edge velocities
    - increase noise shielding
  - increased size to
    - recover aerodynamic performance
  - reduced deflection to
    - prevent divergent gap flow

- development within DLR-project LEISA (2005-2009)



classical slat device

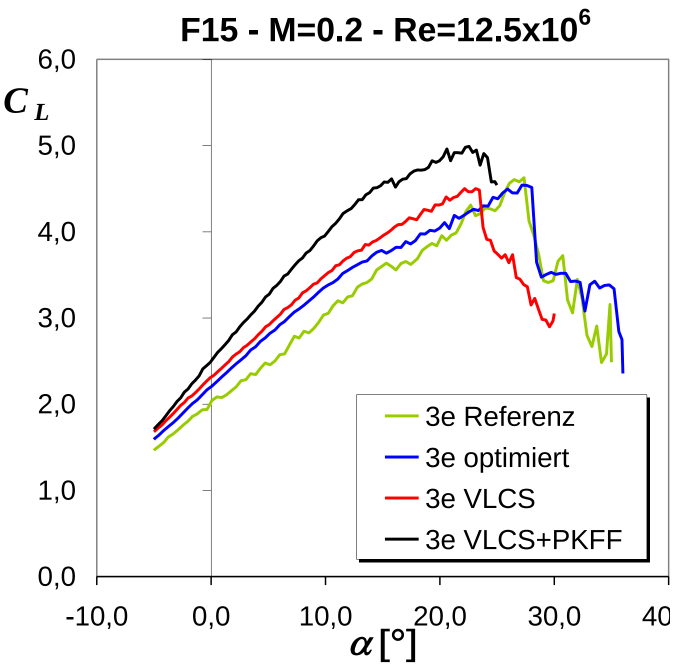


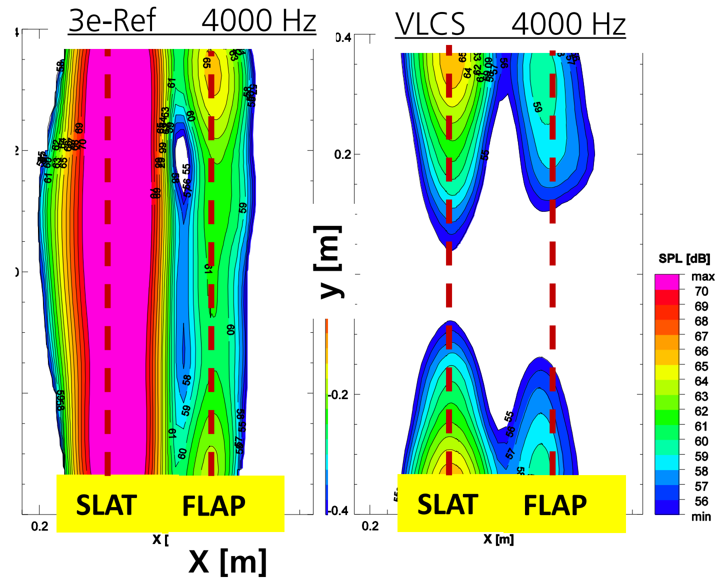
very long chord slat

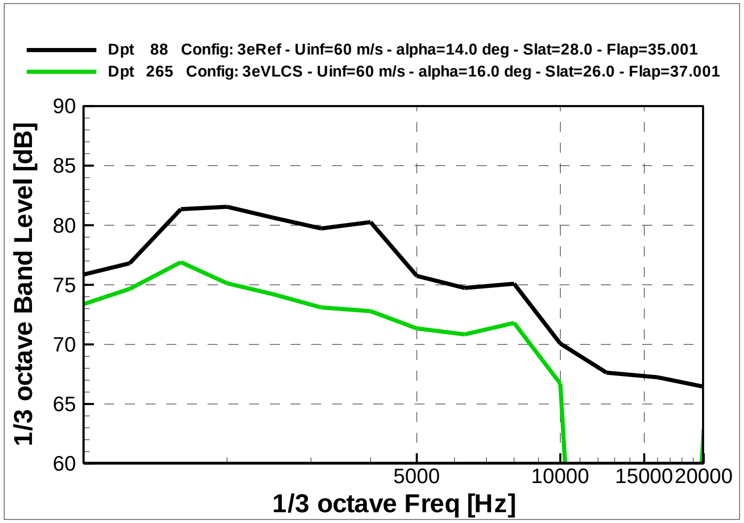
LEISA

Noise Reduction at Leading Edge Devices proof of concept

- the VLCS achieves
  - aerodynamic performance similar to classical slat device
  - broadband noise reduction of up to 7 dB







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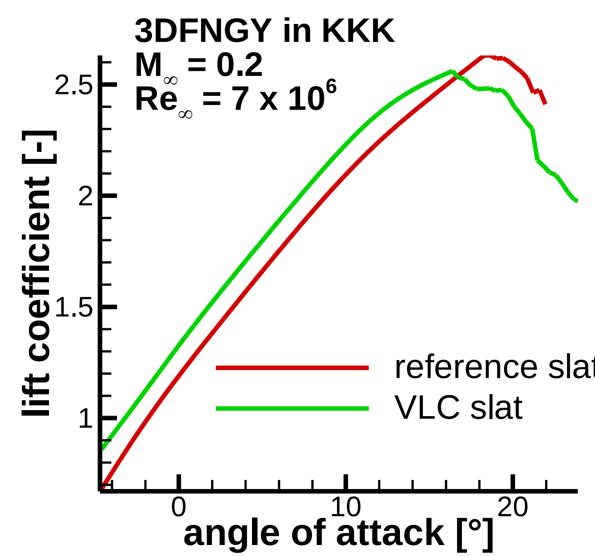
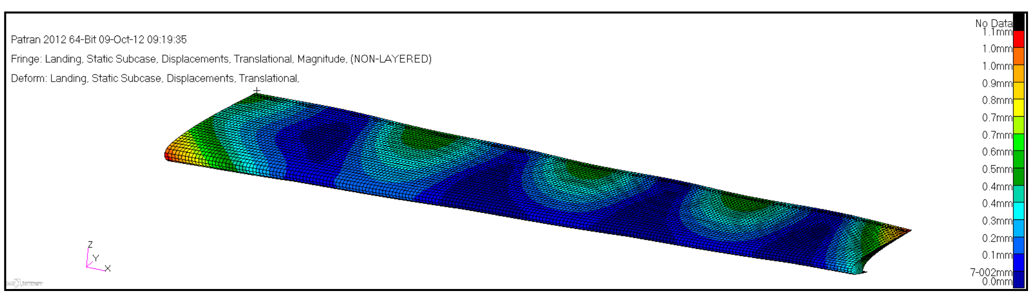
Noise Reduction at Leading Edge Devices Concept verification

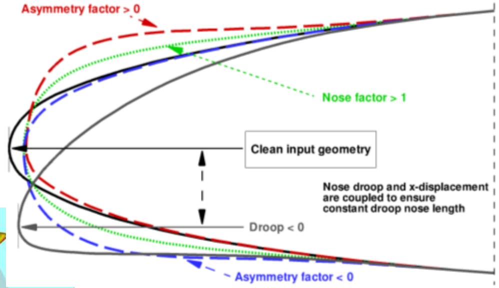
- DLR F15-VLCS transfered to 3D FNG-wing
- assessment of aerodynamic and aeroacoustic performance
- structural low weight CFRP concept developed, including
    - thermal isolation & impact shield
    - electrical isolation
    - heating blanket
    - erosion shield

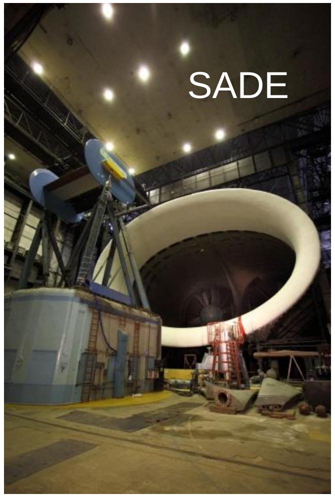


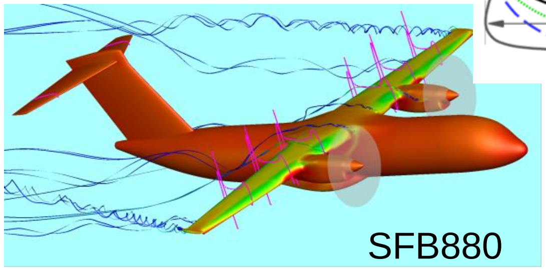


Adaptive High-Lift Systems
smart leading edge – a history

- first patent by Pierce – US patent 3.716.209 (1973)
- aerodynamic concept design – LEISA (2005-2009)
- first structural concepts – SmartLED (2007-2010)
- large scale demonstration – SADE (2008-2012)
- 3D implementation and Validation – SLED (2011-2013)
- follow-ons: SARISTU, CleanSky-SFWA
- concept followed also in SFB880 for Coanda-Wing (2011-)







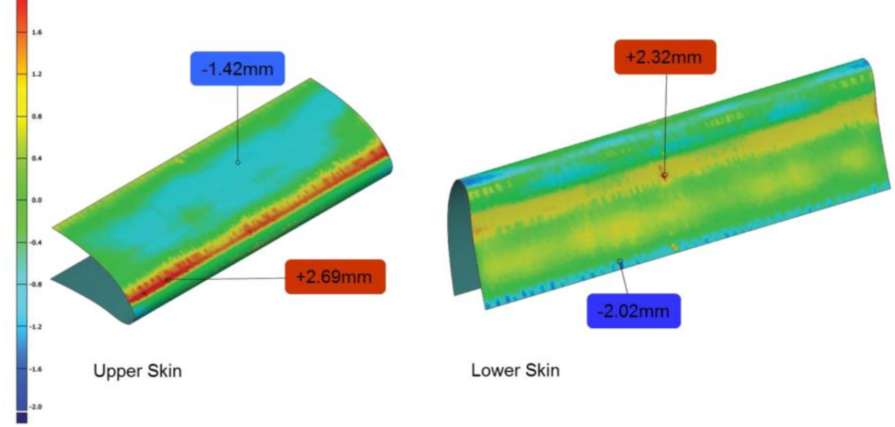
Adaptive High-Lift Systems
smart leading edge – the SADE conclusion

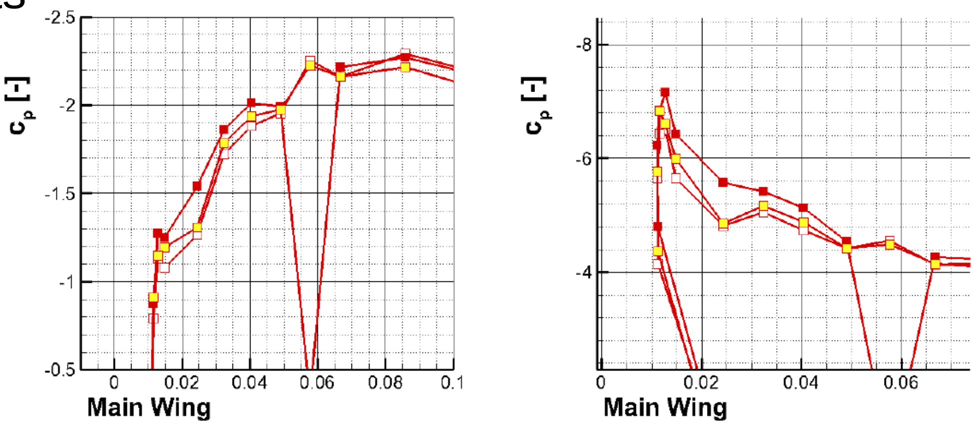
- aerodynamic/structural challenges still exist

- SADE test revealed significant buckling visible in aerodynamic data

- collaborative attempt needed to address aero-structure coupled effects

- Measurements of the SLE Shape, **deformed**





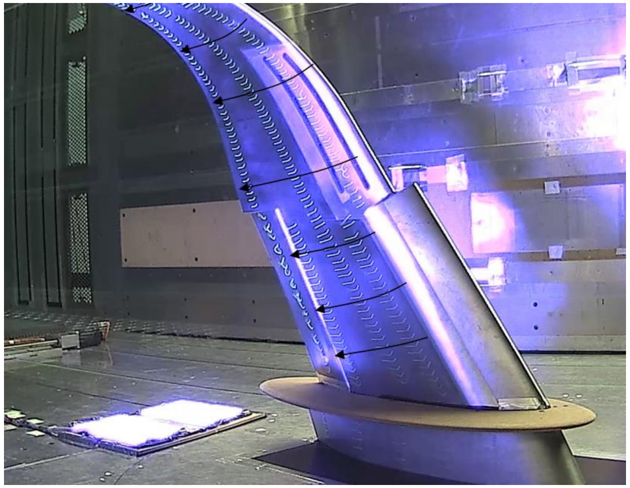
suction peak, incidences 10° (left) and 22° (right)

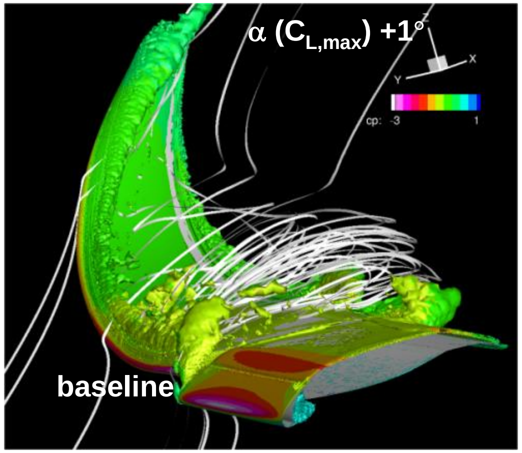
Active Flow Separation Control

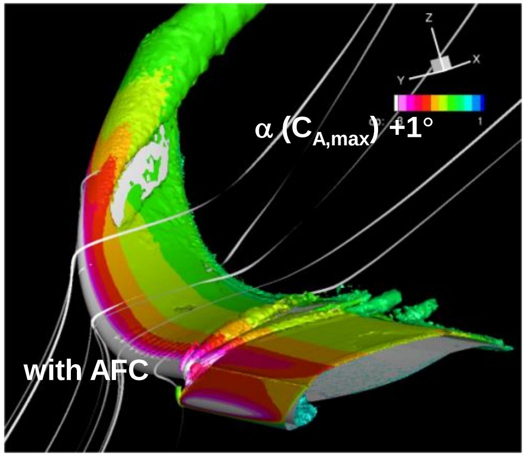
MOVE.ON

local application of active flow separation control

- non-planar wing shapes prevent usage of passive high-lift devices
- use of local flow separation control to prevent drag increase due to local flow separations



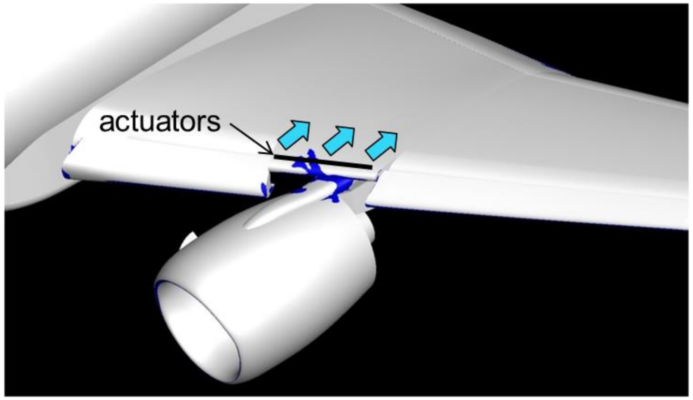


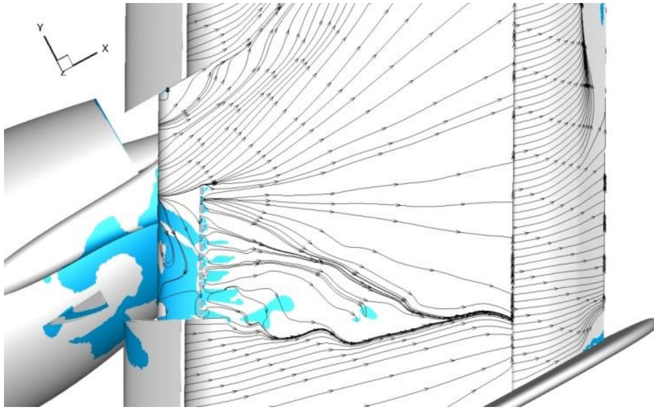


Active Flow Separation Control

local application of active flow separation control

- increase in engine size for fuel reduction implies large cut-out in leading edge devices
- use of local flow separation control at remaining clean wing leading edge to prevent early stall onset downstream of engine
- large scale demonstration within AFLoNext in TsAGI T-101 tunnel (24x14m²) in 2017





Summary

- although long time in service and highly matured, high-lift systems offer plenty of topics for aerodynamic research

- current challenges

    - several new technologies need enabling high-lift solutions
        - Krueger devices for laminar wing
        - VLCS for noise reduction
        - smart (adaptive) devices
        - active flow control for local flow improvements

- what is required today?
    - consideration of constraints from different disciplines
    - multi-disciplinary assessment
    - higher maturity of solutions

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