MAE2 - Aviation & Environment

Role of Aerodynamics

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08/09/2022

This lecture is heavily based on slides of: S. Bonnet, S. Bedoin, (Supaero 3A)

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SUPAERO

Contribution to overall course structure

- **Block 1: Aircraft operations, aircraft manufacturer regulations, EU programmes, aviation trajectory (11h)**
  - Aviation trajectory – CAST (3h - ISAE)
  - EU research programs & Institute Sustainable Aviation (1 + 1h – ISAE)
  - Operations & optimization (3h – ENAC)
  - Environmental regulations in Industry (3h - Airbus)
- **Block2: Engineering leverage (13h)**
  - New aircraft architectures – engineering impact (2,5h – Airbus)
  - Emerging propulsion and aero-propulsion synergy (2,5h – Safran)
  - Aerodynamics & Acoustics (3,5h – ISAE - ECL)
  - Eco-Structural design, LCA materials & manufacturing (4,5h – ISAE – Airbus)
- **Block3: Group Project**
  - Mixed international - majors groups (5-6 students, overall 150h)
  - Targeted at technical or system issues to review/compare, analyze, to model, with env. ass.(e-taxiing, biomimetism, SAF, multimodal, …)
  - Outputs: poster and oral

Lecture scope & definition

- ❑ Motivations: to survey aerodynamics contributions to lowering environmental impact through higher L/D configurations
- ❑ Skills targeted: (a) understanding of key aerodynamics drivers at stake, (b) acquisition of key aerodynamic leverages to lower environmental impact and identification of inter dependency of engineering strategies;
- ❑ Contribution to multi-choice questions exam

- ❑ Proposed definition:

Predict and master air behaviour around an aircraft

to

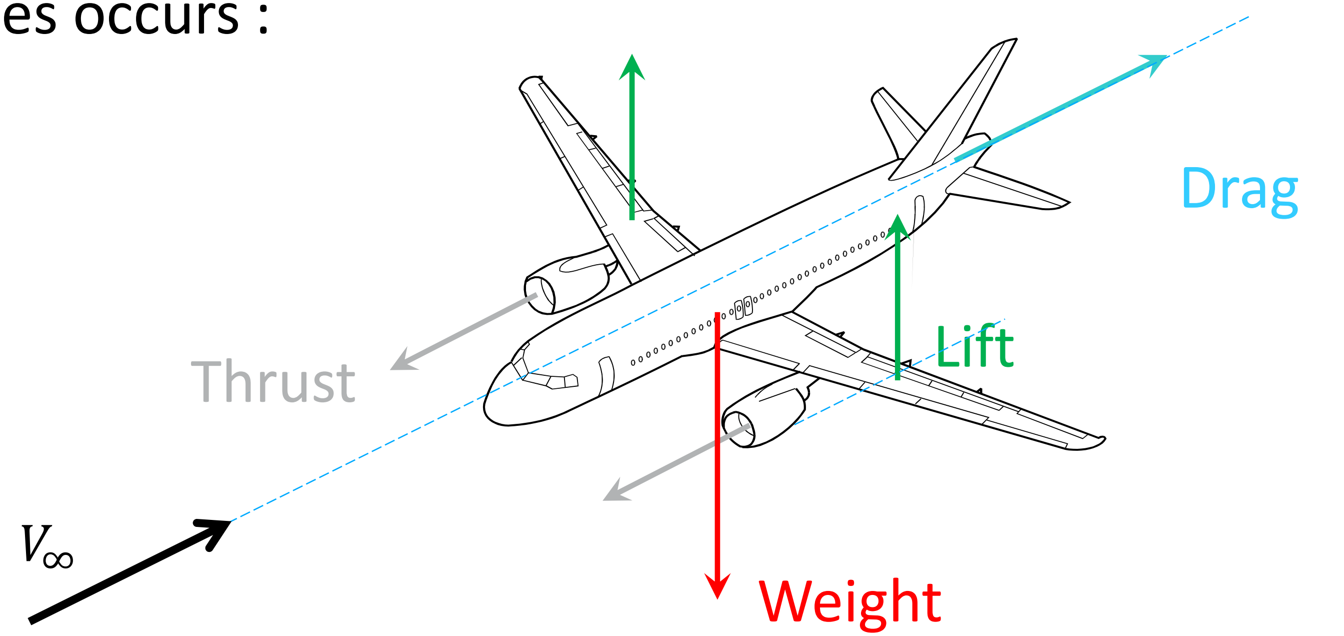
Ensure aircraft safety and performance

Contents

1. **Scope of Aerodynamics**
2. **Configuration Aerodynamics**
3. **Friction management**
4. **Separation control**
5. **Shock control**
6. **Conclusion**
7. **Complements**

1. Scope of Aerodynamics: link to flight

On an aircraft at cruise (constant speed) an equilibrium between the forces occurs :



The **lift force is only due to pressure action**, and is the built-up of infinitesimal pressure forces acting on the airframe, essentially on the wing.

The **drag force is the sum of infinitesimal shear forces** acting on the whole airframe, **plus some pressure contribitions**. See **7. Complements** for reminder of basics.

1. Scope of Aerodynamics: from forces to coefficients

- By definition: The drag is colinear with the freestream velocity $\overrightarrow{V_\infty}$

  The lift is perpendicular to the freestream velocity

  The Angle of Attack, AoA, is set between $\overrightarrow{V_\infty}$ and a reference line of your aircraft or component

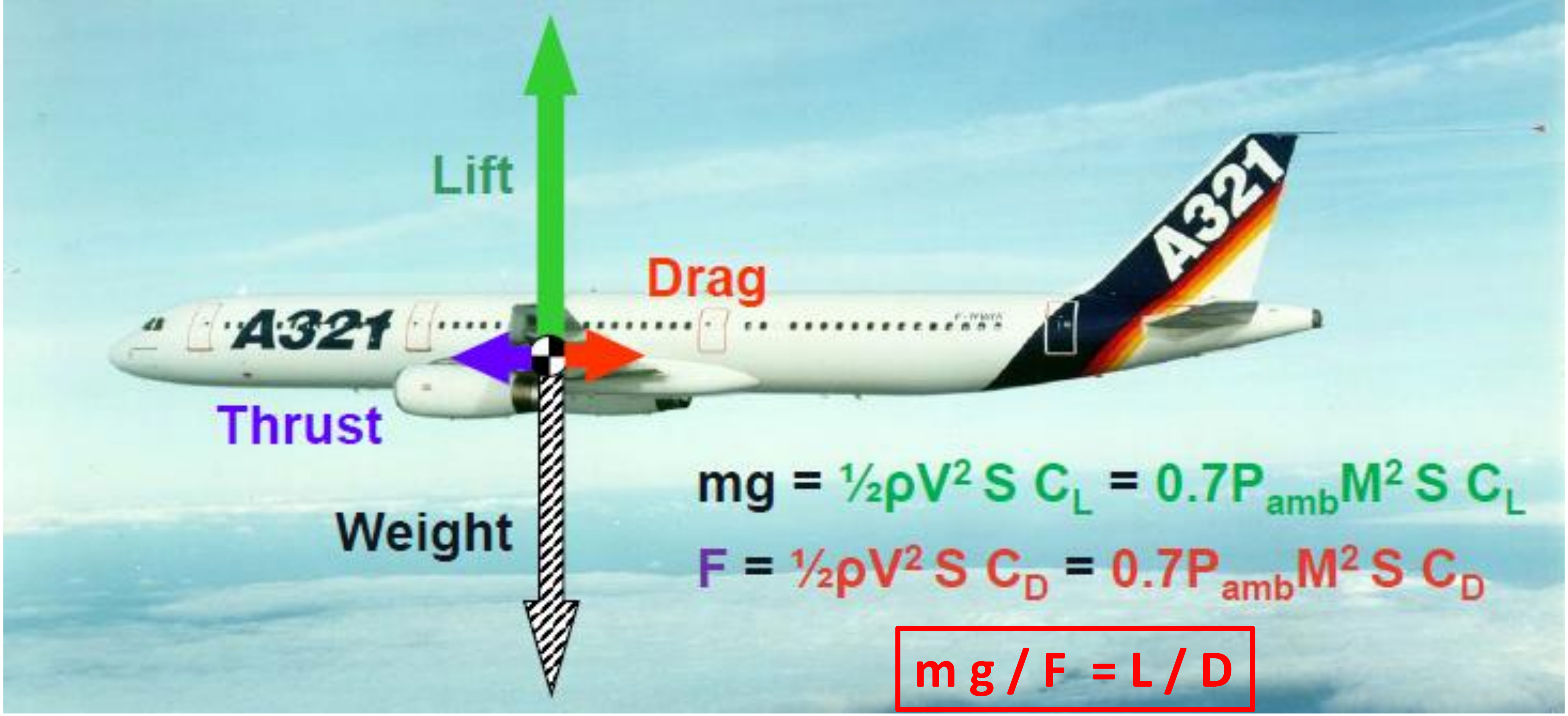
- The aerodynamic forces (and moments) can be demonstrated to expressed as:

$$L = 1/2\rho_\infty V_\infty^2 S_{ref} \boxed{C_L} \qquad D = 1/2\rho_\infty V_\infty^2 S_{ref} \boxed{C_D}$$

- Coefficients reflect the nature of the body (1D → 3D), the shape, the flight domain (Re, Mach), the environment (background turbulence, icing/insects..., vibration...)

1. Scope of Aerodynamics: link to performance (cruise)

- Aircraft to fly at given altitude and speed ➔ Lift = Weight
- Stabilized Flight level to be maintained ➔ Thrust = Drag



$$mg = \tfrac{1}{2}\rho V^2 S\, C_L = 0.7 P_{amb} M^2 S\, C_L$$

$$F = \tfrac{1}{2}\rho V^2 S\, C_D = 0.7 P_{amb} M^2 S\, C_D$$

$$\boxed{m\,g / F = L / D}$$

1. Scope of Aerodynamics: cruise key drivers

One for all / All for one
BREGUET-LEDUC formula

Aerodynamic efficiency

Structural efficiency

$$\text{Range} = \frac{\text{Mach} \times \boxed{\text{L/D}}}{\text{Engine specific consumption}} \times \text{Log} \frac{\text{Take-off weight}}{\text{Landing weight}}$$

Engine efficiency

- It fixes trades between disciplines
- Trades are varying with aircraft and mission

For an A380, for example
1% drag ~ 1.6 tons

Extension to electric Systems, and inversed & linearized:

$$\Delta M_F = \underbrace{\Delta M_S\left(e^{\frac{ctg}{f}}-1\right)}_{Mass} + \underbrace{\Delta D_S \frac{f}{g}\left(e^{\frac{ctg}{f}}-1\right)}_{Drag} + \underbrace{\frac{\kappa}{3600}\frac{\Delta P_S}{\eta_e}\frac{f}{cg}\left(e^{\frac{ctg}{f}}-1\right)}_{Electric}$$

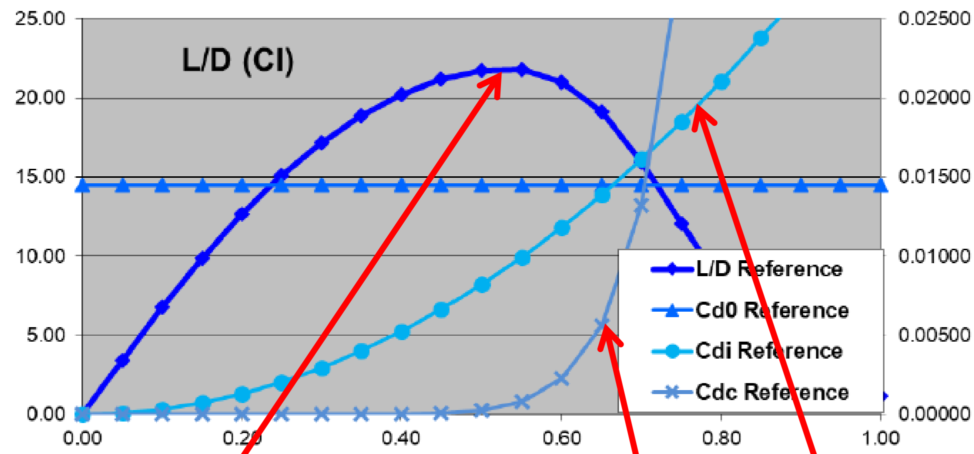
1. Scope of Aerodynamics: important parameters

$$C_{D0} = \sum_{Components} Kf \cdot Cf \cdot \frac{Swet}{S_{ref}}$$

Induced: $C_{Di} \sim \frac{Ki}{\pi AR} C_L^{\ 2}$

$$\frac{L}{D}\max inc. = \boxed{\frac{L}{D}\left(C_{L\,opt}\right)} = 0.5\sqrt{\frac{\pi AR}{Ki \cdot C_{D0}}}$$

$$\frac{L}{D}\max inc. = 0.5 \cdot \boxed{span}\sqrt{\frac{\pi}{Ki \cdot \Sigma\boxed{(Sw \cdot Kf \cdot Cf)}}}$$



« Ideal » flight « point »

Wave drag drag

Lift induced drag

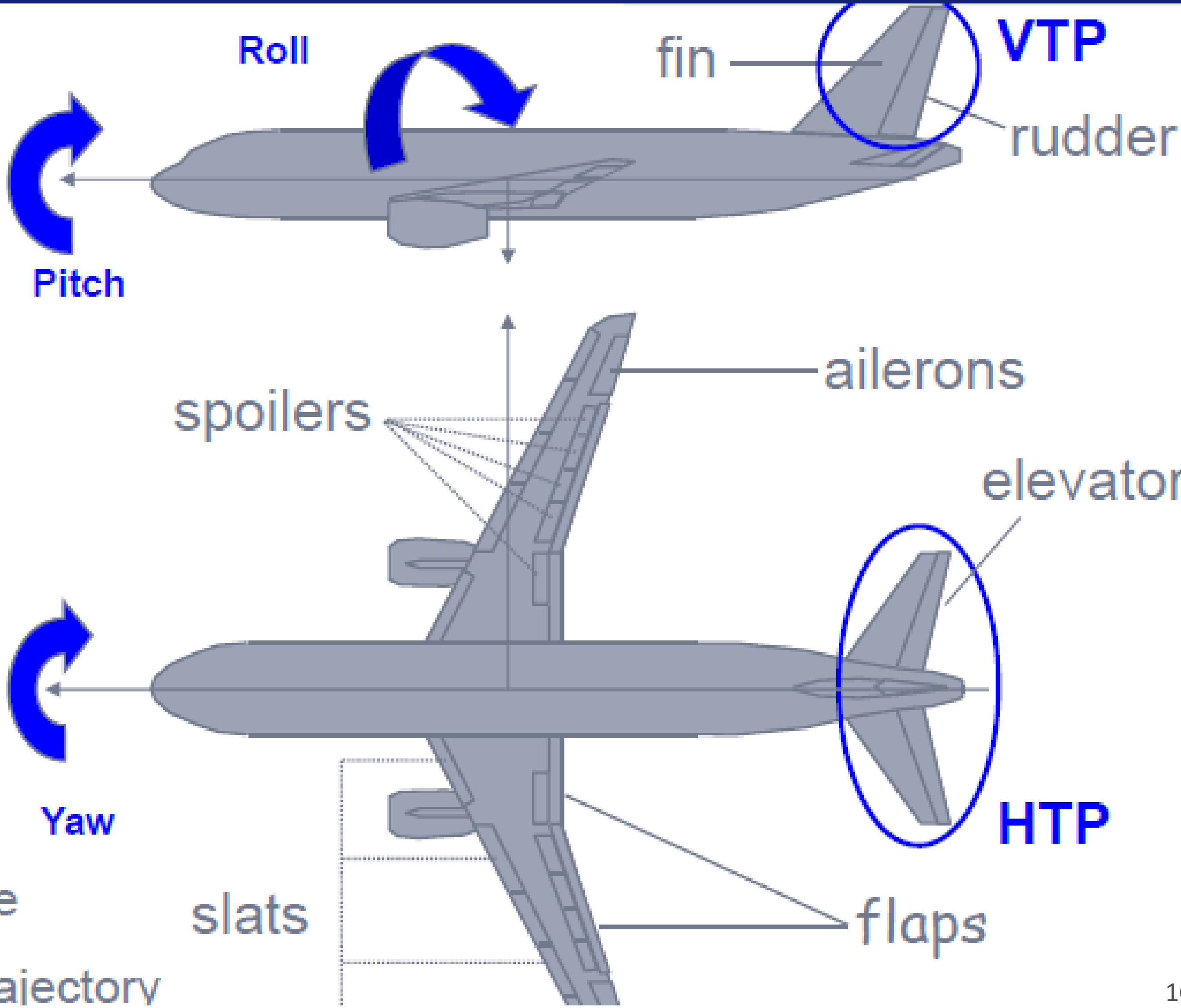
Drag breakdown specific to each design

1. Scope of Aerodynamics: link to AC control

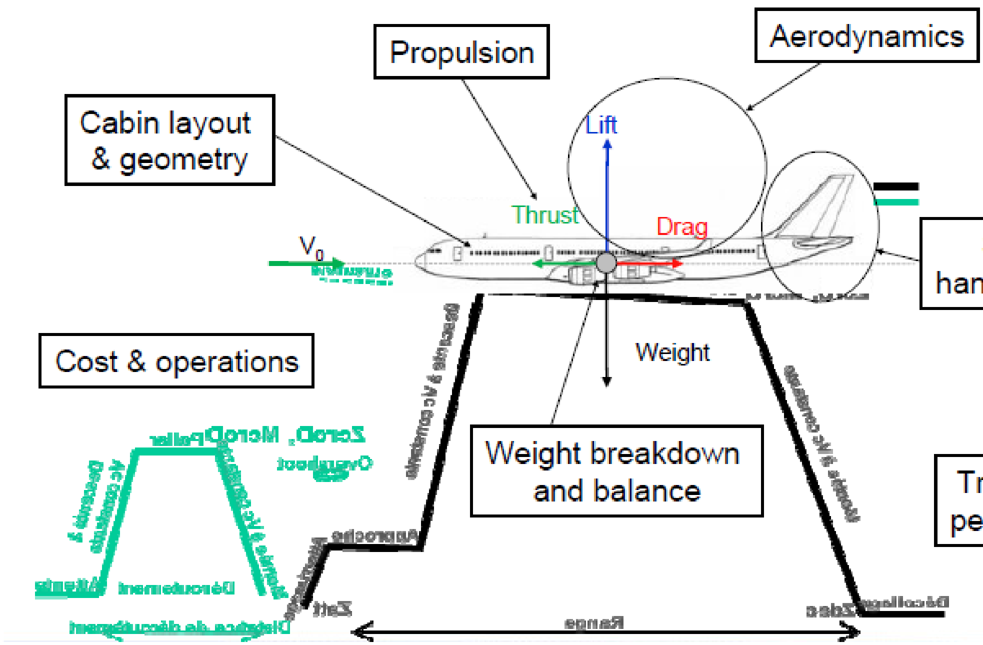
For straight and steady level flight, flight controls are deflected in order to achieve moment equilibrium.

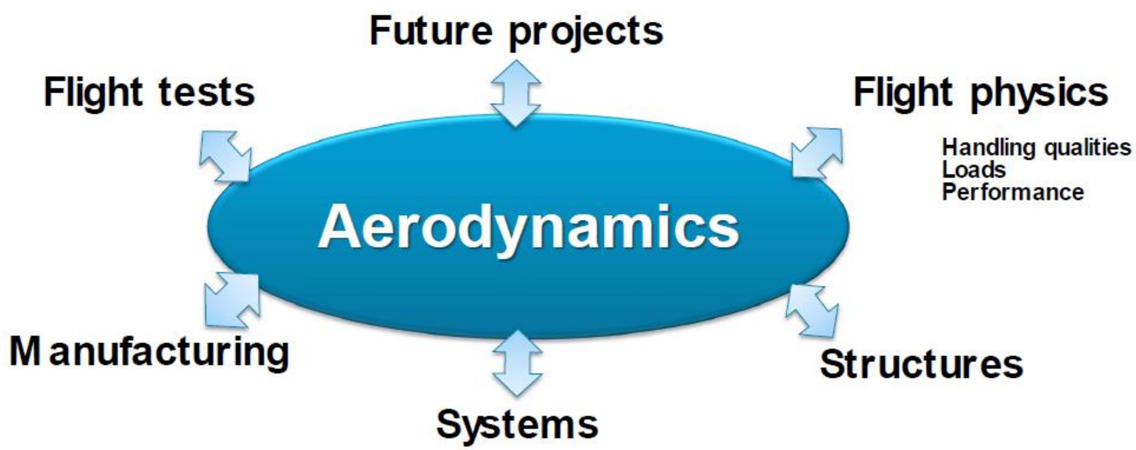
For maneuvers, flight controls are deflected to create moments in order to position the aircraft versus air speed vector.

Controls
→ Moments
→ Rotations
→ Lift force
→ Trajectory



1. Scope of Aerodynamics: link to mission & interactions





1. Scope of Aerodynamics: snow ball effect

- The need for efficient design techniques : ***new technologies***
  - A simple example : use of composites for the vertical tail
  - Direct consequences : weight is reduced, CoG position is moved forward
  - Indirect consequences :
    - Less lift is required -> the wing size can be reduced
    - Stability is increased -> HTP and VTP size can be reduced
    - Dry weight is reduced, drag is reduced -> fuel consumption is reduced
    - Less thrust is required -> engine can be downsized
    - MTOW is reduced -> less lift is required
      - -> entering snowball effect

1. Scope of Aerodynamics: requirements & outputs

❑ **Aerodynamics Requirements:**

1. Airworthiness &Operations rules
2. Customer requirements – product development
3. Resulting from **T**op **L**evel **A**ircraft **R**equirements

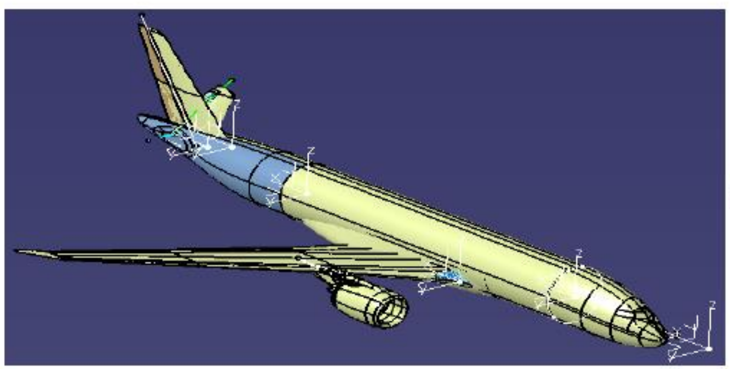
Requirements:

HIGH SPEED requirements
- **Payload (Pax + Cargo)**
- **Nominal Range**
- **Cruise Speed**
- Cruise Ceiling (Thrust, Buffeting)

LOW SPEED requirements
- **Take-Off distance**
- **Approach Speed**
- **OEI ceiling**

❑ **Outputs:** **DESIGN** & **DATA**

Shapes



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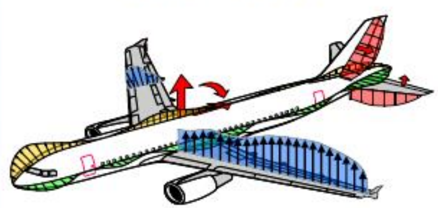
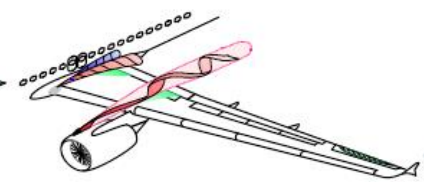
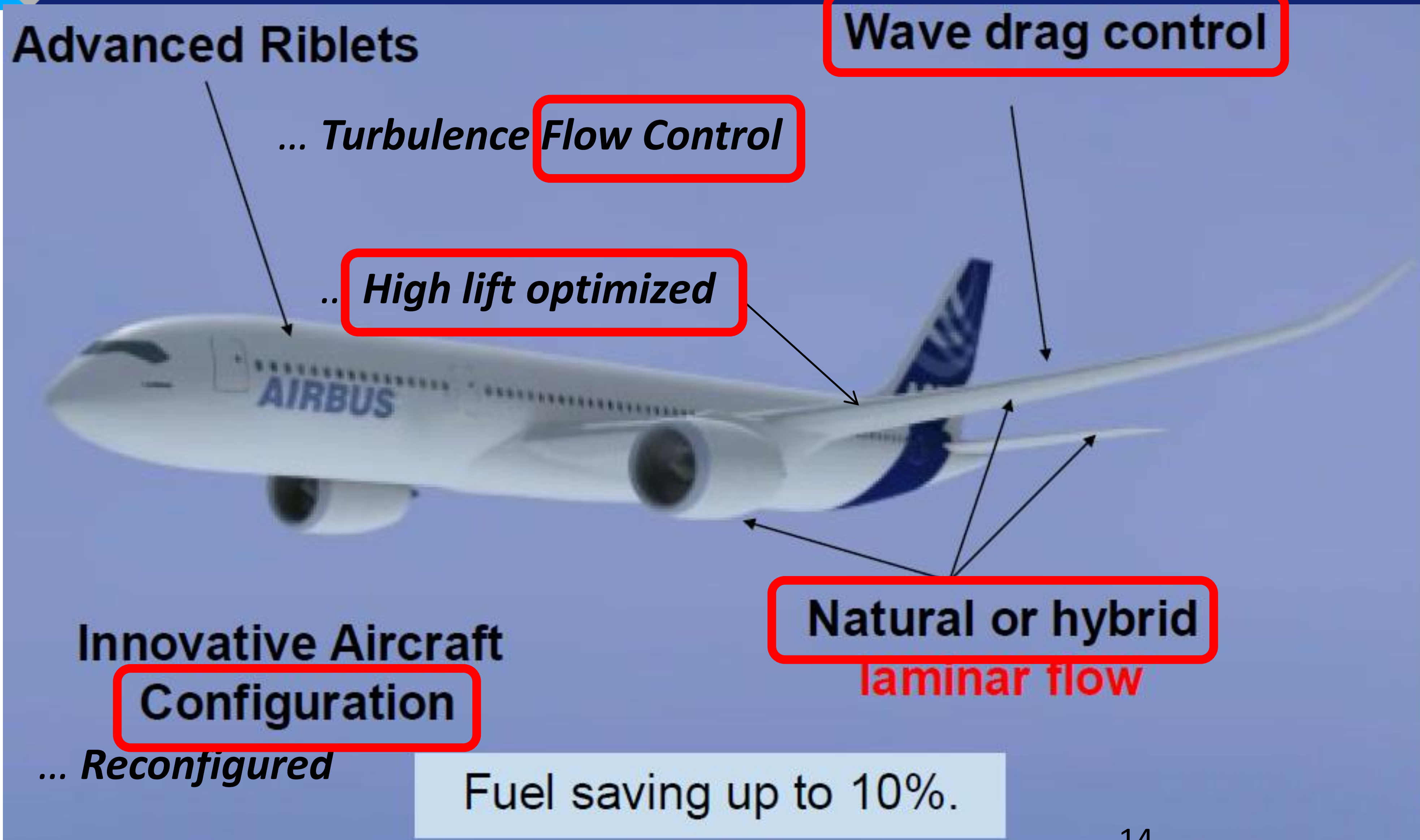


For Performance

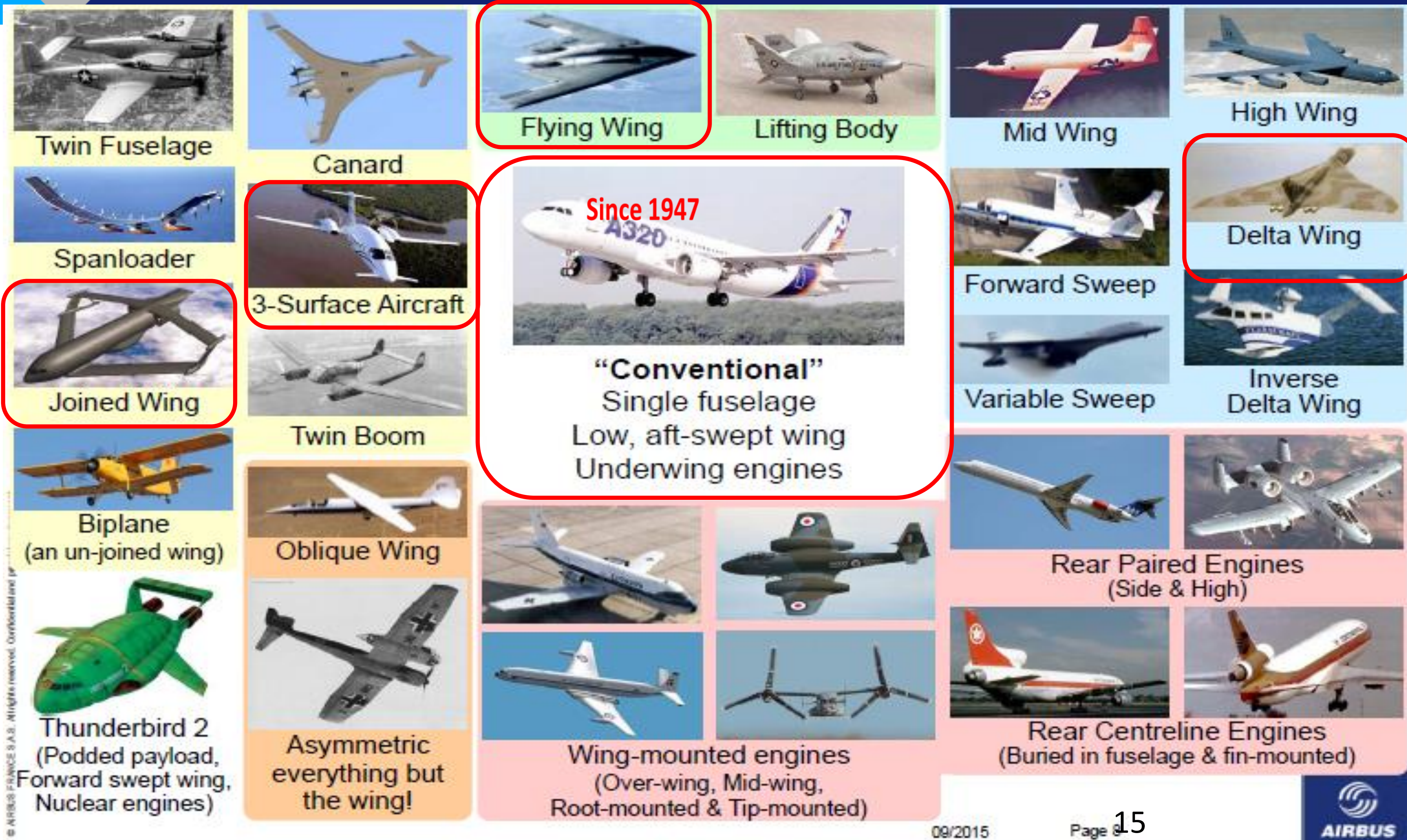


For Handling qualities

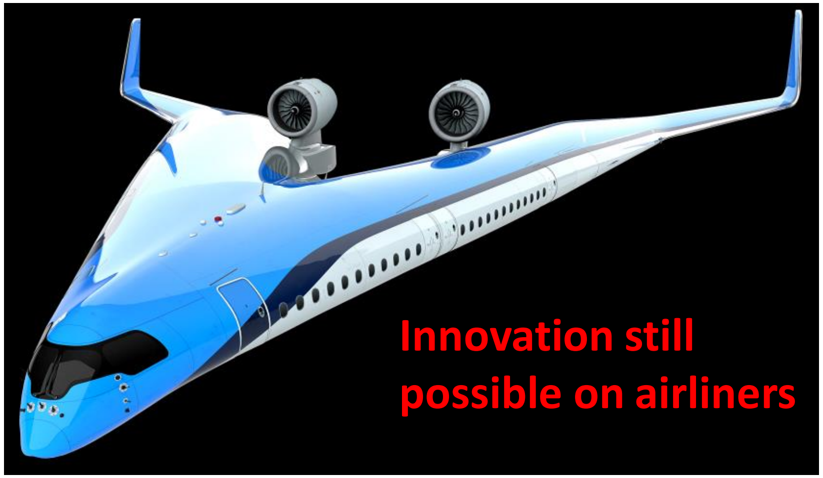
1. Scope of Aerodynamics: example of point of view

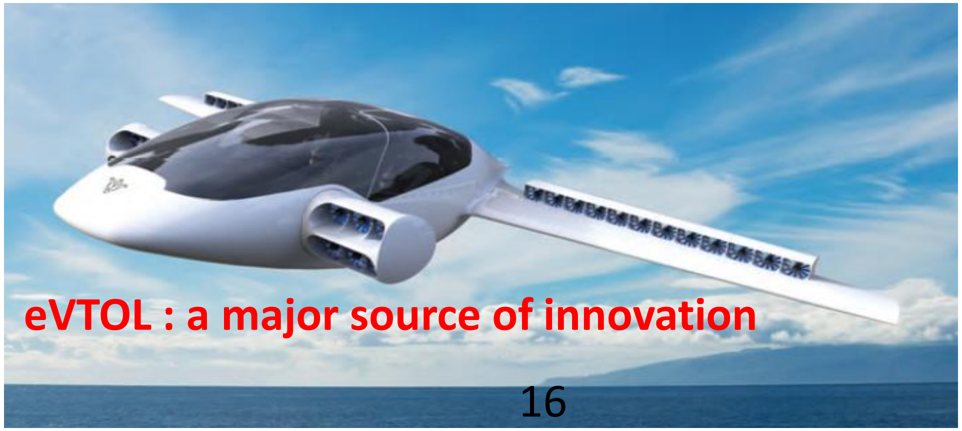


2. Configuration Aerodynamics: weight of history



2. Configuration Aerodynamics: history in move

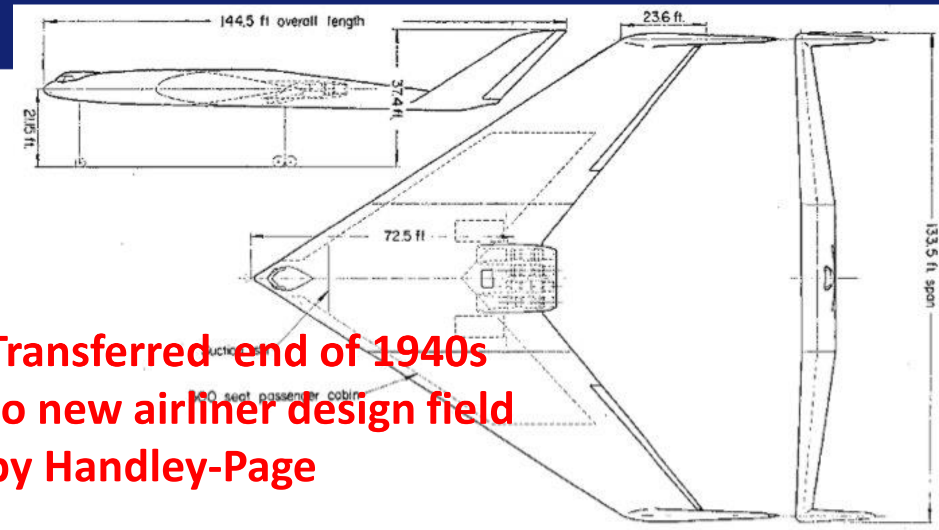




2. Configuration Aerodynamics: path to full integration

Works initiated in 1920s by Lippisch & Espenlaub

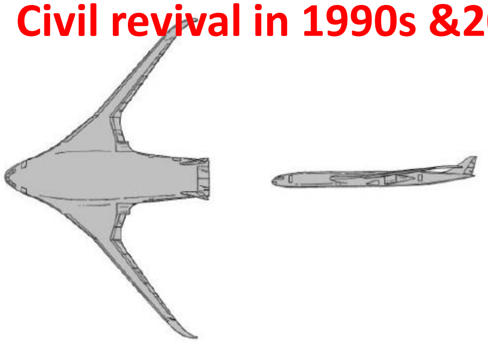
First military design by Horten brothers (Ho 229)



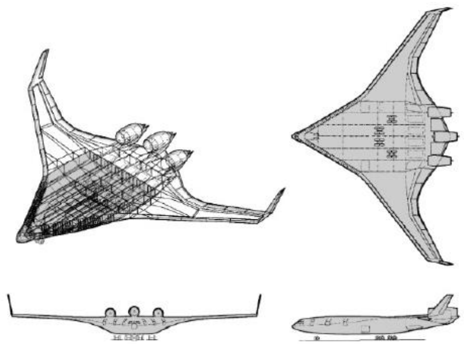
Transferred end of 1940s to new airliner design field by Handley-Page

Full or partial integration of paylod, lift, propulsion & control functionalities

Civil revival in 1990s &2000s



(a) BWB configuration, first proposed by McDonnell & Douglas in 1998 [LPR98]



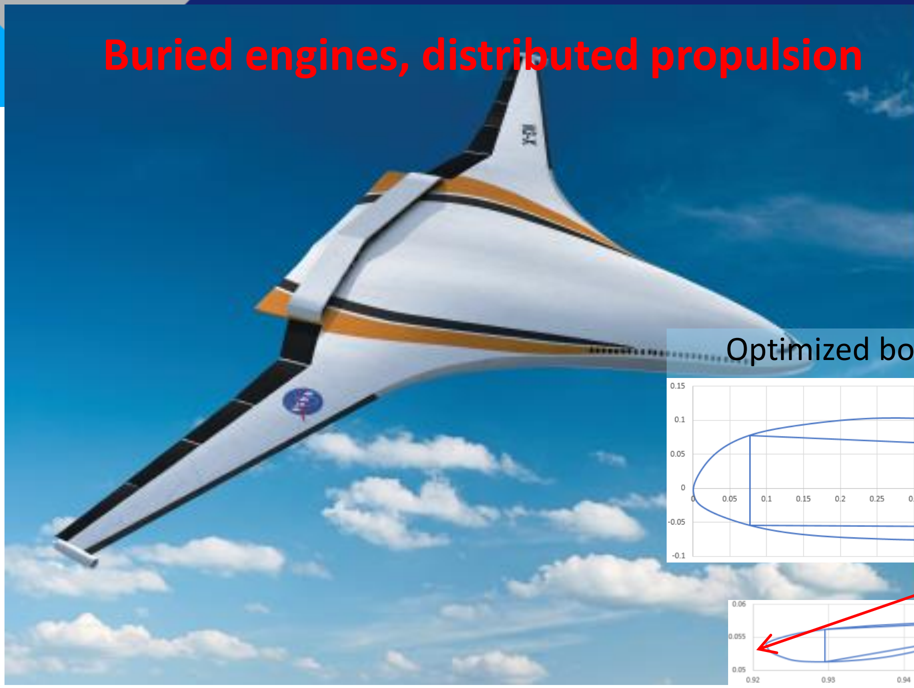
(b) More advanced BWB concept, proposed by Boeing in 2004. This configuration is aimed to carry 450 passengers [Lie04].

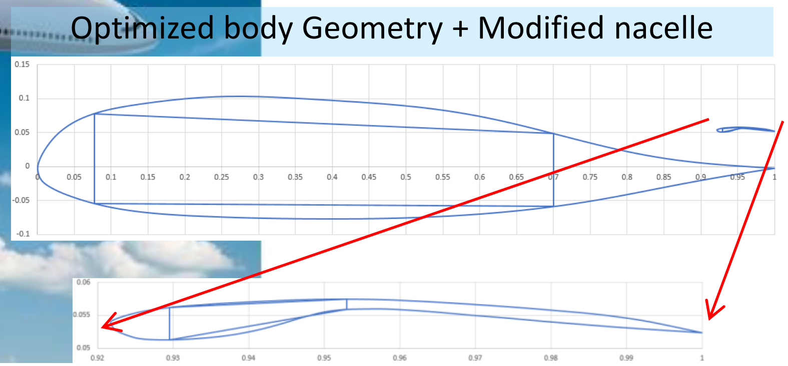
Low detection bomber B2

More review: https://www.researchgate.net/publication/292680419_Review_of_evolving_trends_in_blended_wing_body_aircraft_design/figures?lo=1

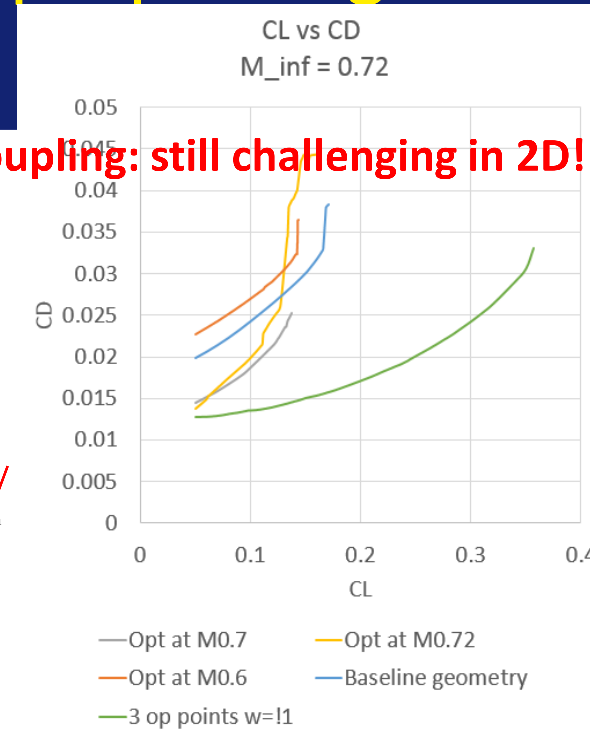
2. Configuration Aerodynamics: full aero-prop. integration

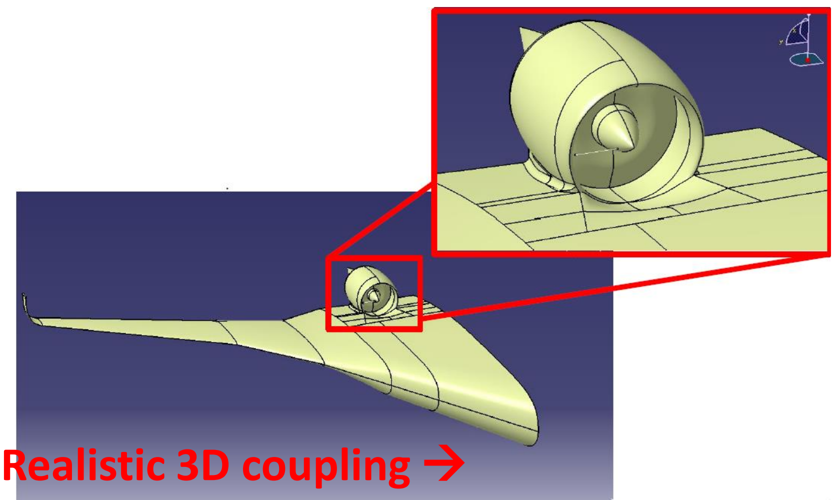
Buried engines, distributed propulsion



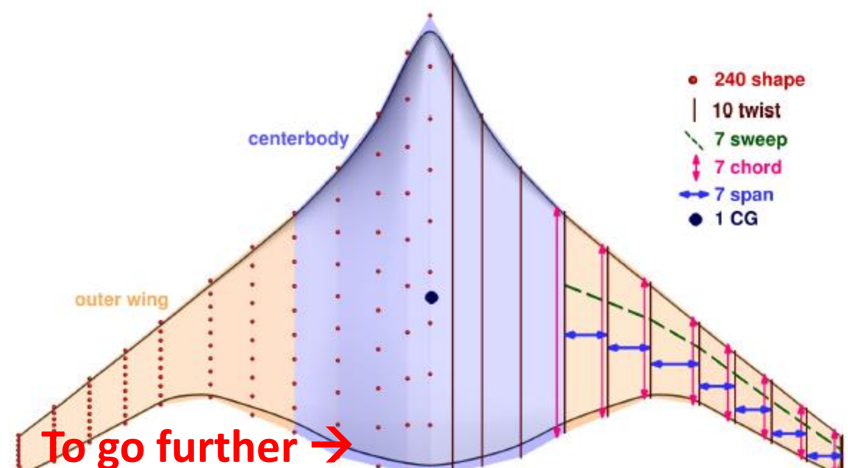


High coupling: still challenging in 2D!



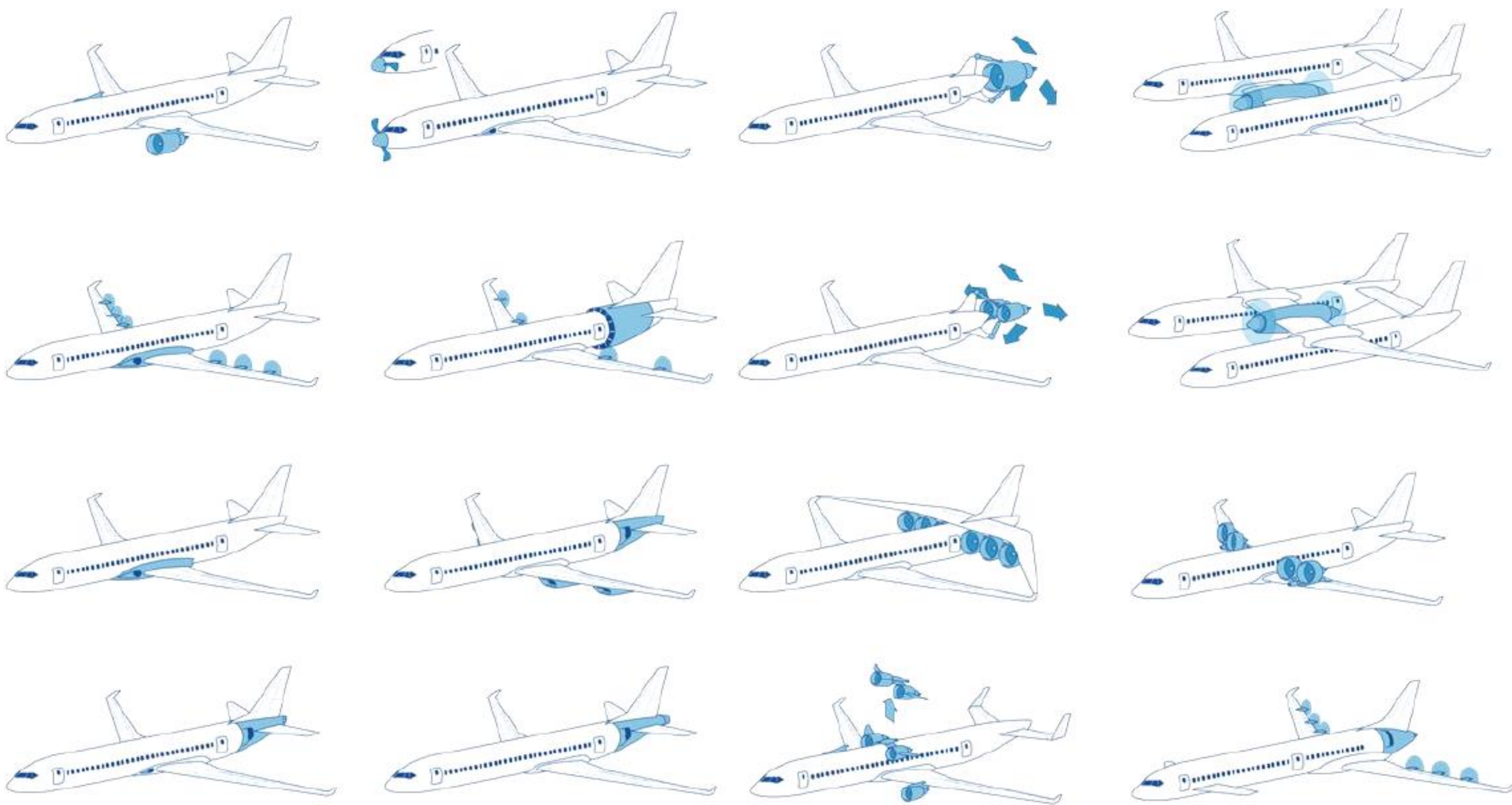


Realistic 3D coupling →
Full CFD RANS with low order model for engine



To go further →
Full CFD RANS optimization (Liu & Martins 2014)

2. Configuration Aerodynamics: full aero-prop. integration



YXFO / NT – ISAE 2021-2022 – MsC MAE – 2MAE006 - Aviation and environment – Emerging propulsion

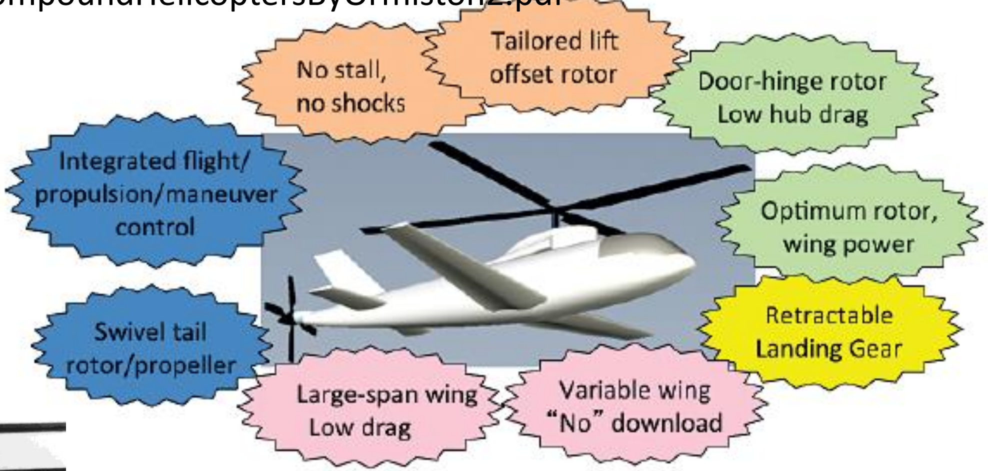
SAFRAN

- ❑ Each of those installations will bring its own type of aerodynamical issue(s)
- ❑ Analysis required can range of 1D to full 3D unsteady analysis

2. Configuration Aerodynamics: rotor based configuration


https://vtol.org/files/dmfile/48CompoundHelicoptersByOrmiston2.pdf

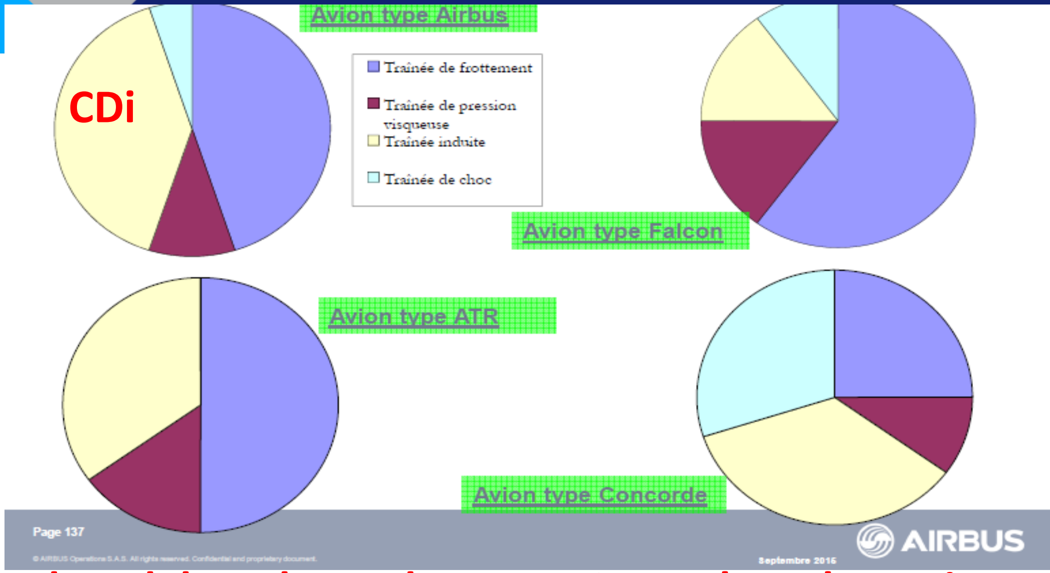
X^3



- ❑ **3D – vortex dominated flows -, usually unsteady**
- ❑ **CFD challenging – leading to LES like simulations. Requirement on model reduction strategy**
- ❑ **Experimental work: costly**

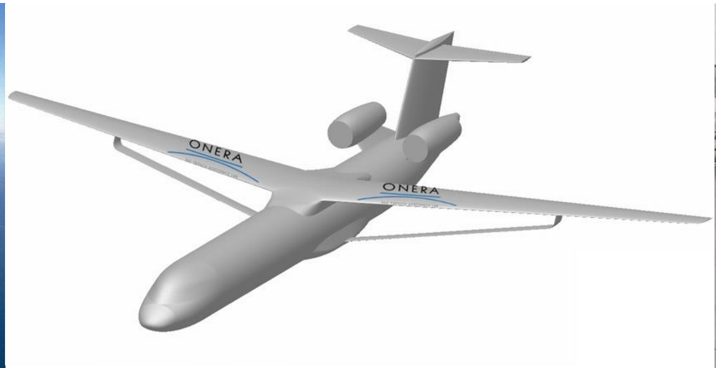
eVTOL.news

2. Configuration Aerodynamics: race to high AR (1)



Induced drag dependent on AC type but always important

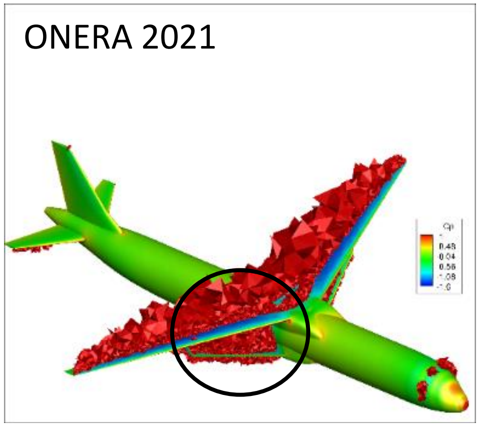
High aspect ratio (>50!) essential to very high performance sailplanes
L/D max > 70

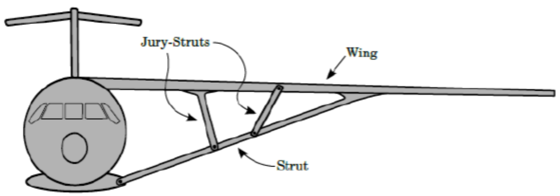


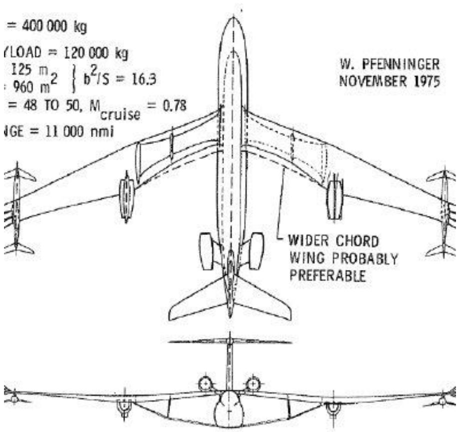
From hints of Pfenninger (1970s) and Hurel-Dubois (1960s), NASA-Boeing Sugar Volt or ONERA-Albatross projects: what would be an ideal AR and how to design it (strut, foldable ..)?

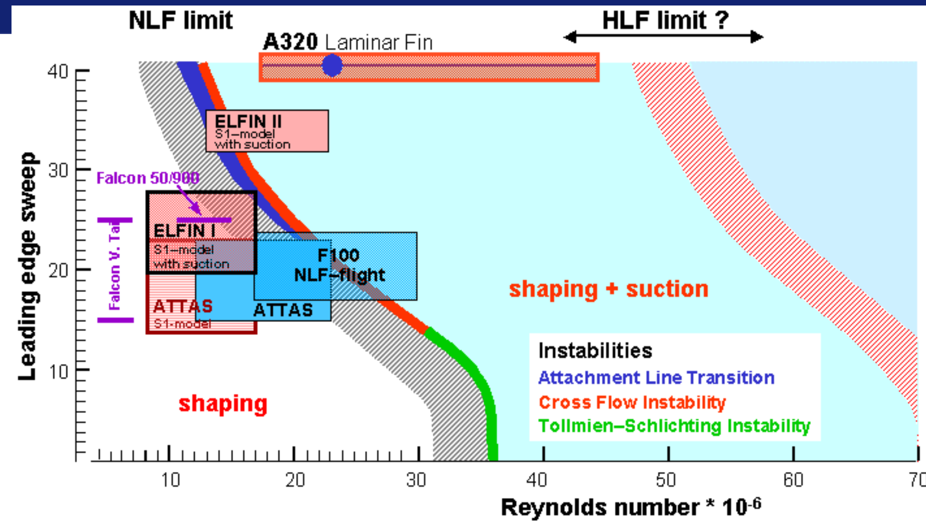
2. Configuration Aerodynamics: race to high AR (2)

New aerodynamic interactions: wave drag to optimize (Euler & RANS)



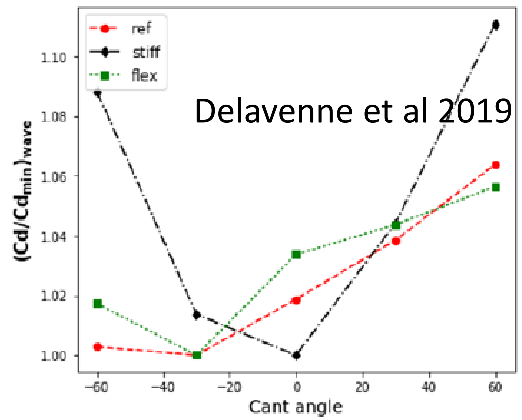


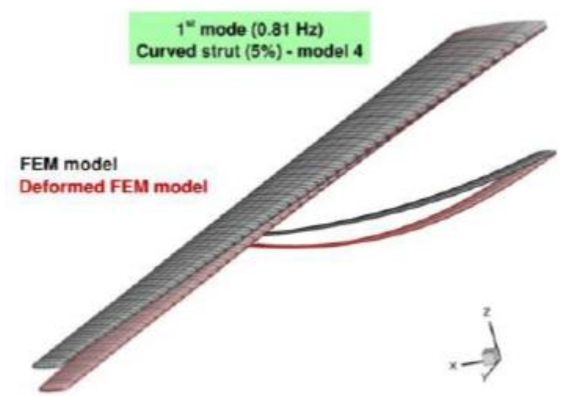




Schrauf 2005

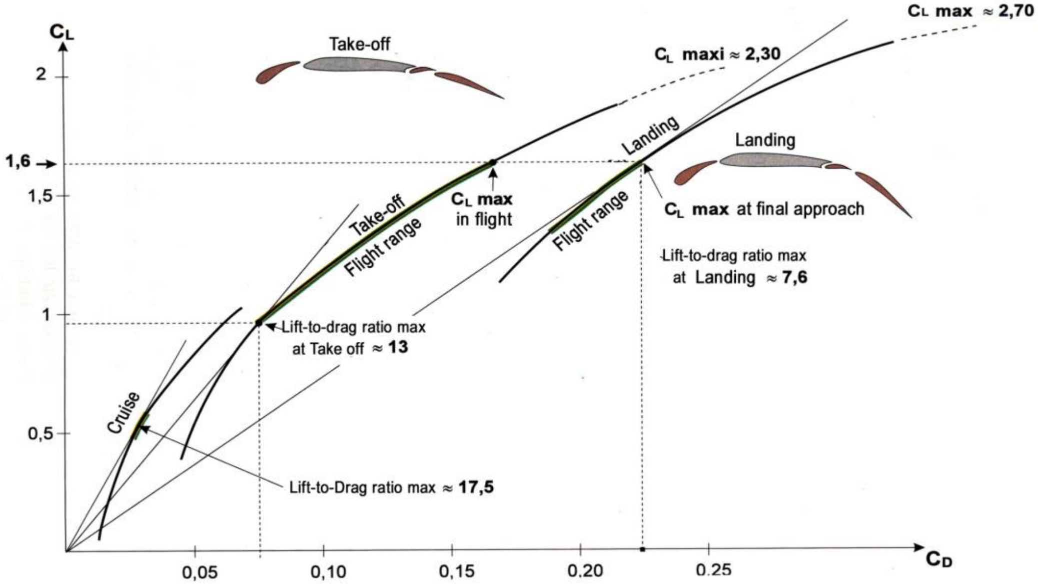
New opportunities: shorter chords, lower Reynolds numbers → instability & transition simulations & wind tunnel tests

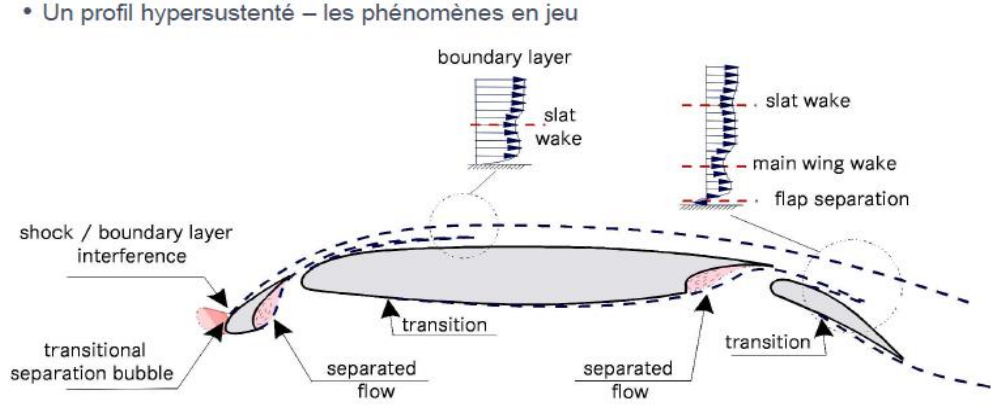




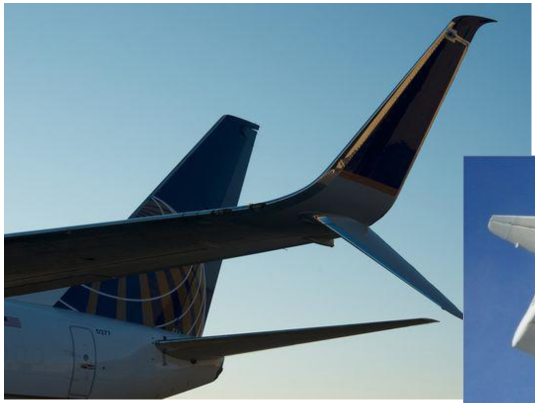
New challenges: proeminent aero-structural coupling. A/C are now optimized fully deformed!

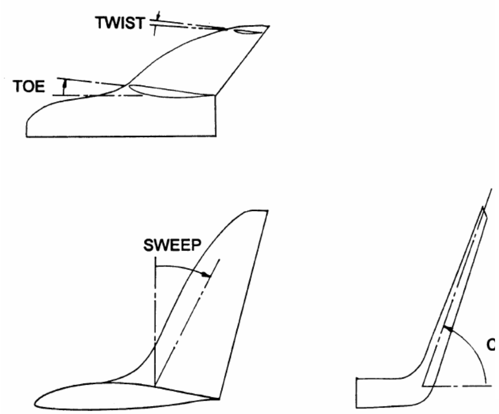
2. Configuration Aerodynamics: other routes to high AR

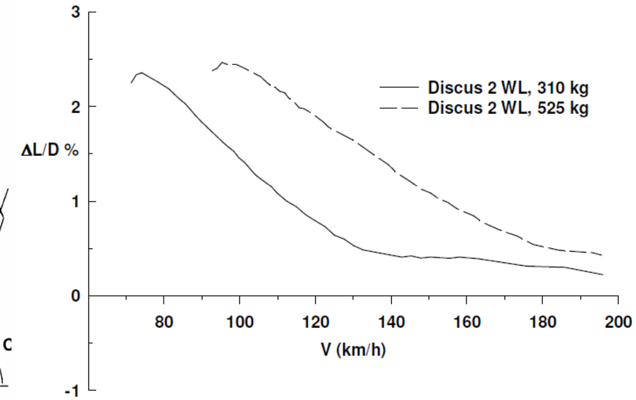




At constant span, a key enabler to higher AR are High Lift Devices: still challenging to optimize in 2D, highly specialized for 3D-transonic configurations





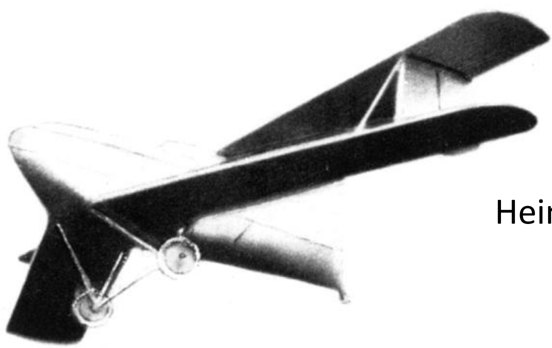


NASA-TN-D-8260 by Richard T. Whitcomb

https://hub.united.com/en-us/news/company-operations/pages/new-split-scimitar-winglets-take-flight-on-united-737800.aspx

Many forms of winglet are now available but always need to assess: sensivity to Mach, Reynolds, aeroelastic behavior and weight penalty

2. Configuration Aerodynamics: wider range of designs



Heinkel-Lippisch 1932

Fielding 2012

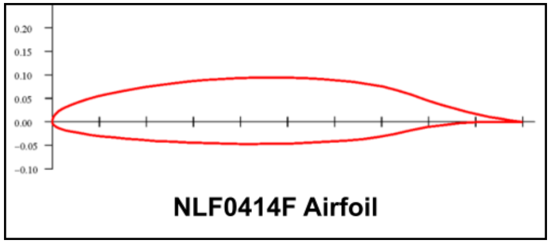
BT Aero

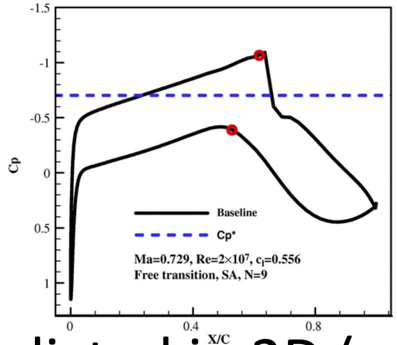
Driven by: higher AR, stiffer-ligter wing, combined wing – HTTP – VTP roles

Reminder: All those designs not only rely on better aerodynamics but also on overall design (weight, propulsive efficiency)

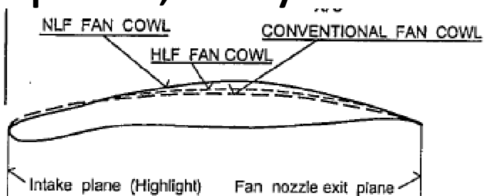
3. Friction management: extended laminarity, 2D

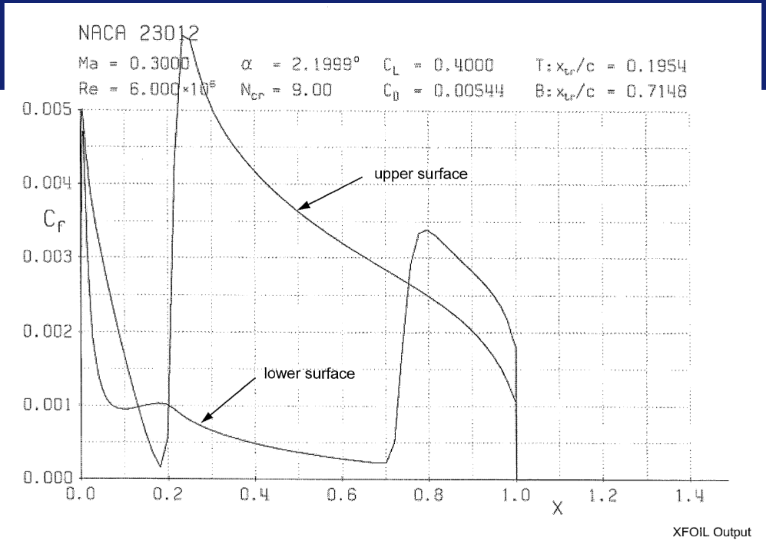
- ❑ Lower skin friction in laminar flows
- ❑ Natural (or forced) instability leads to Turbulence: accelerating a BL can postpone Transition….





- ❑ Well understood and predicted in 2D (no sweep) and low forcing: good integration with wing design (XFLR5… but much less in standard CFD)
- ❑ Paradox: because of operational difficulties & crude oil price, very limited use beyond GA…



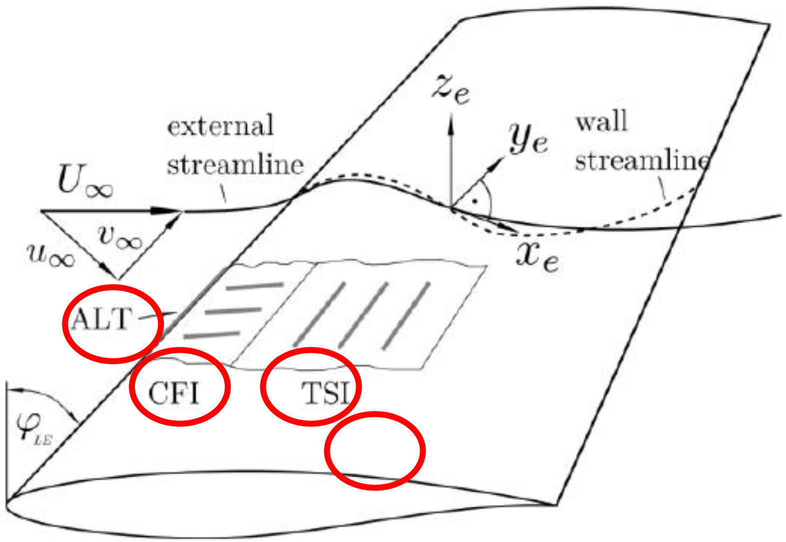


Date	Aircraft	Test Configuration	LF Result	Comments
1940	Douglas B-18 (NACA) 2-engine prop bomber	NACA 35-215 10'x17' wing glove section suction slots first 45% chord	LF to 45% chord (LF to min C_p) $R_C = 30x10^6$	Engine/prop noise effected LF surface quality issues
1955	Vampire (RAE) single engine jet	upper surface wing glove suction - porous surface full chord suction	full chord LF M~0.7 / R_C=30x10⁶	Monel/Nylon cloth 0.007" perforations
1954-1957	F-94 (Northrup/USAF) jet fighter	NACA 63-213 upper surface wing glove suction – 12, 69, 81 slots	Full chord LF 0.6 < M < 0.7 $R_C = 36x10^6$	at M_{local}>1.09 shocks caused loss of LF
1963-1965	X-21 (Northrup/USAF) jet bomber 30° sweep	new LF wings for program suction through nearly full span slots – both wings	full chord LF $R_C = 47x10^6$	effects of sweep on LF encountered
1985-1986	JetStar (NASA) 4-engine business jet	two leading edge gloves Lockheed – slot suction & liquid leading edge protection McDD – perforated skin & and bug deflector	LF maintained to front spar through two years of simulated airline service	no special maintenance required lost LF in clouds & during icing LE protection effective

Bajnath et al, 2004, Review

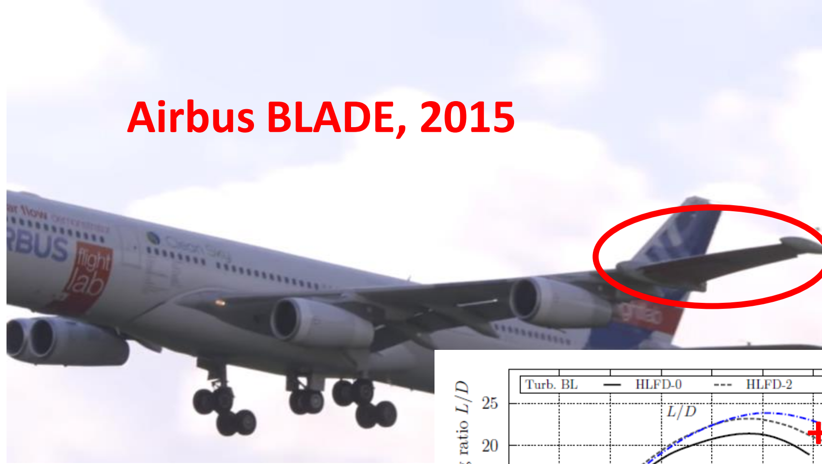
3. Friction management: extended laminarity, 3D

3D: more mechanismes at play

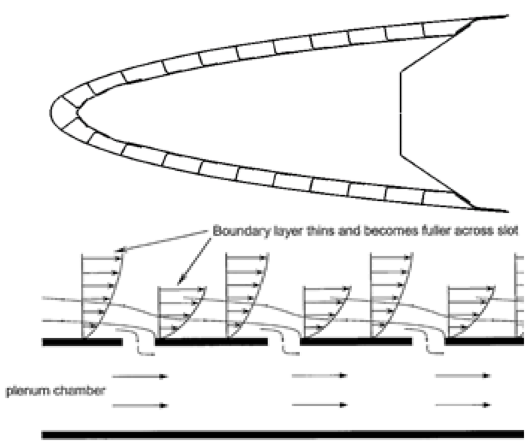


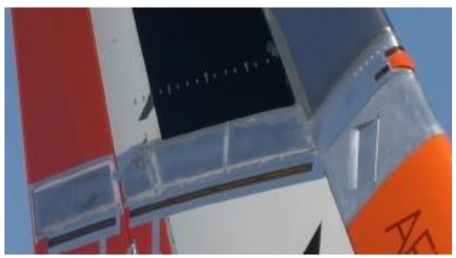
Survey of attachment line flow (ALT), from the 1950-60s

Airbus BLADE, 2015



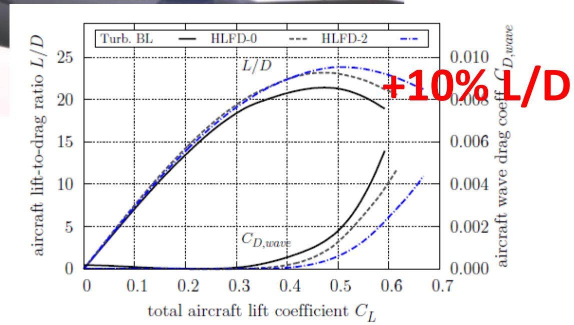
BL Suction: limiting 3D mechanisms





Schrauf 2020

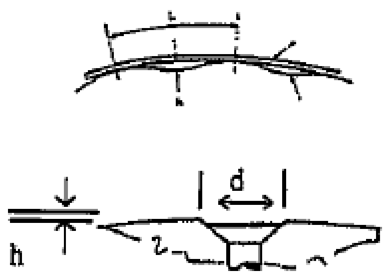
Beck et al., 2018



Within (Re,M, ϕ) limits, use of laminarity down to integration, maturity, operational and cost issues

3. Friction management: extended laminarity, challenges

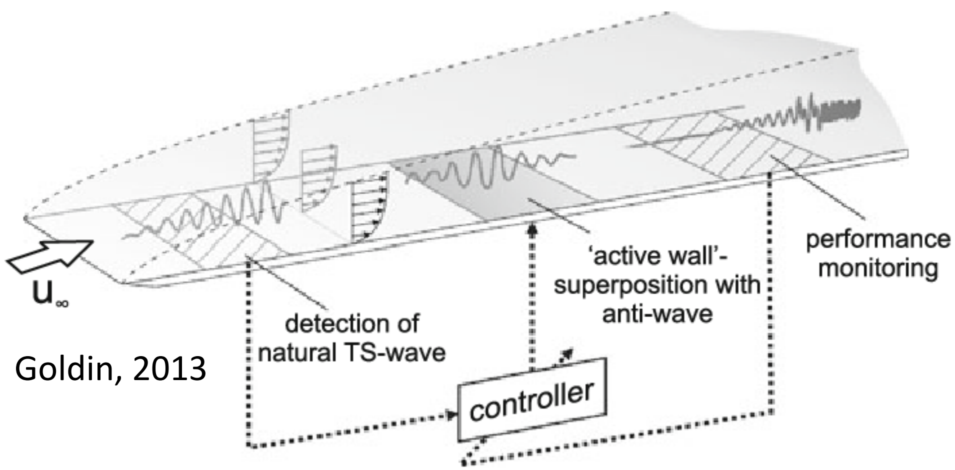
- But requires a smooth surface → manufacturing requirement /operational constraints → cost (initial or operations)



Aerodynamic vs Manufacuring: cost trade-off (Raghunathan 1999)

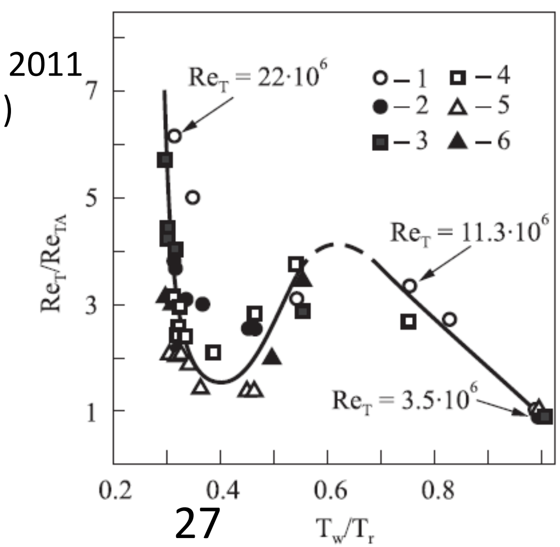
For GA applications: cleaning in flight, temperature (anti-icing)…

- Potential active flow control strategies: wave cancellation, cooling…



Goldin, 2013

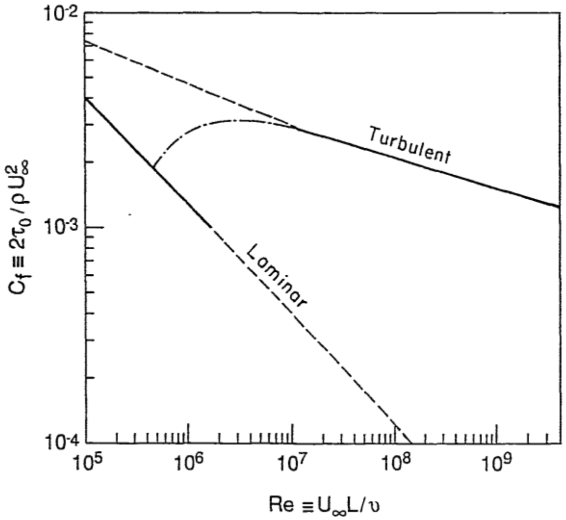
Chernychev, 2011 (supersonic!)



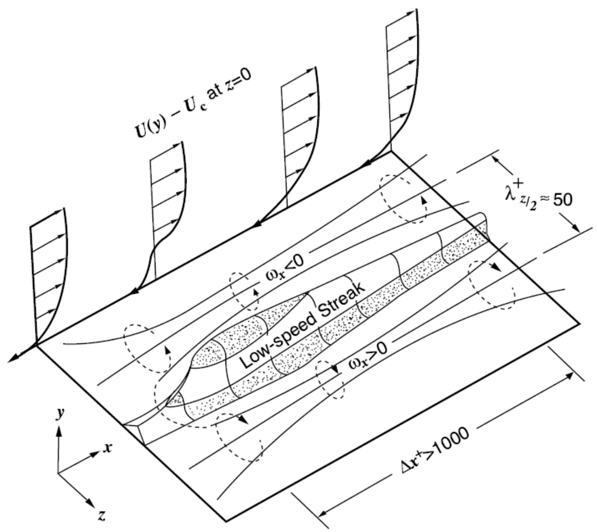
https://www.annualreviews.org/doi/abs/10.1146/annurev.fluid.30.1.1

3. Friction management: basics of turbulent flows

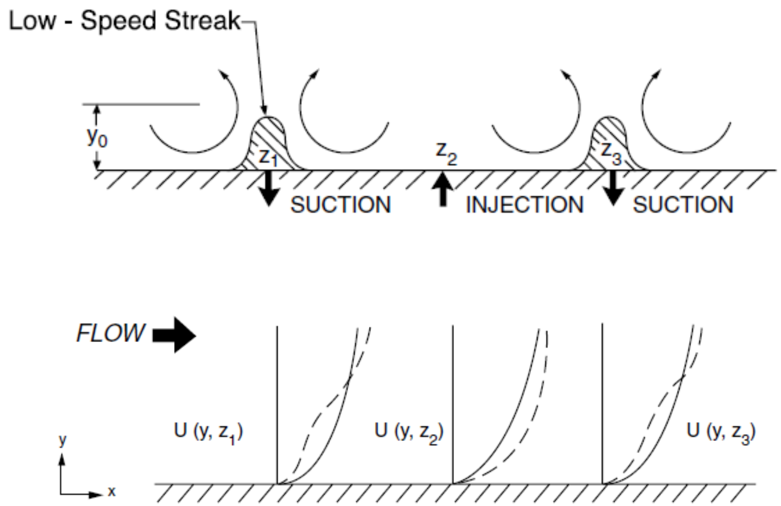
- It is generally accepted that the turbulent boundary layers consist of "coherent motions" (Robinson, 1991), of low momentum fluid which is often associated with streamwise vortices:



Gad-el-Hak, 1998



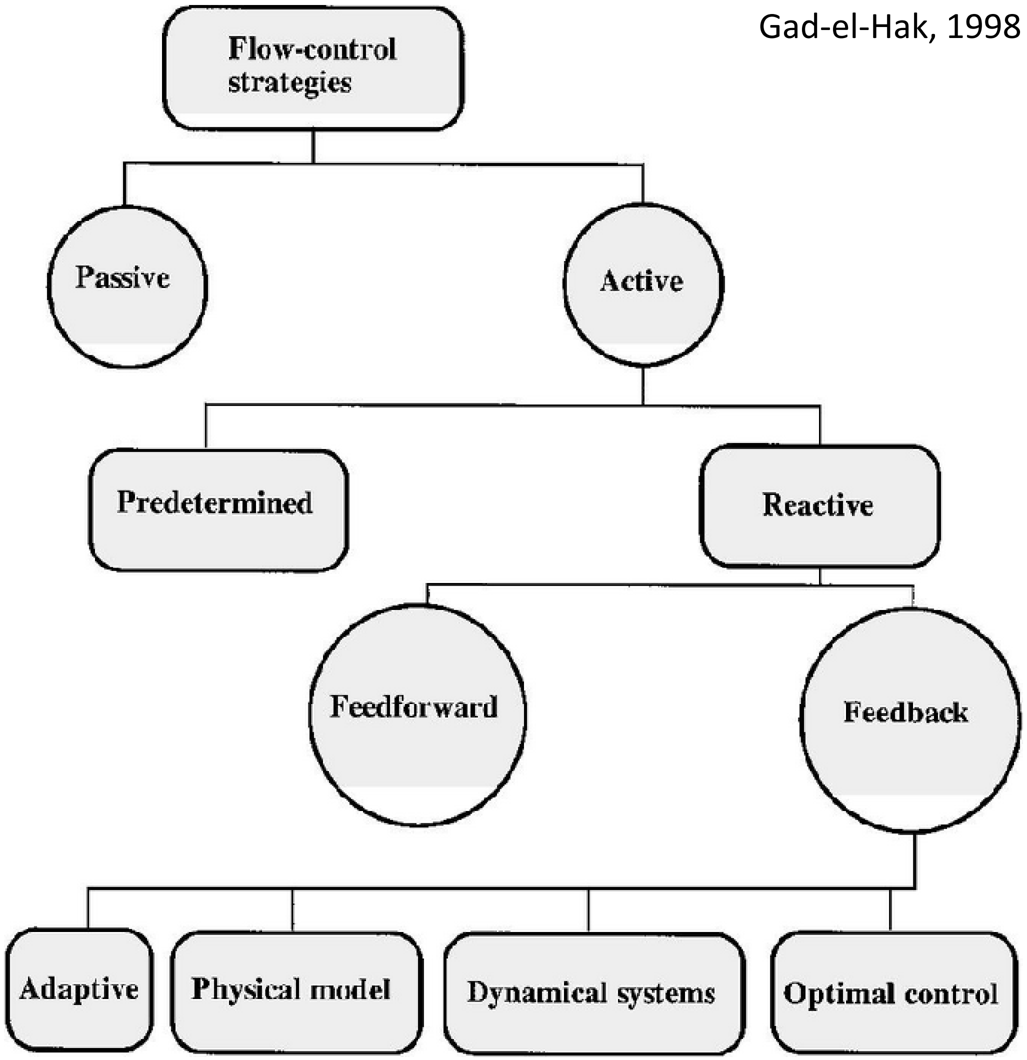
Ghanadi, 2012

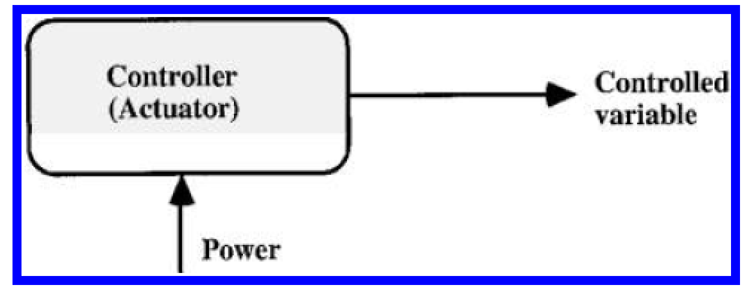


- One possible way to control the turbulence is targeting these structures using flow control strategies

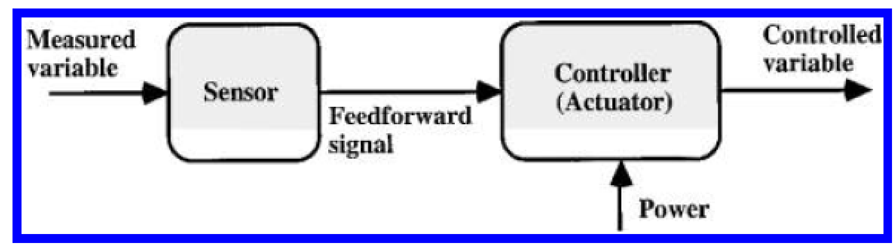
3. Friction management: flow control typology

Gad-el-Hak, 1998

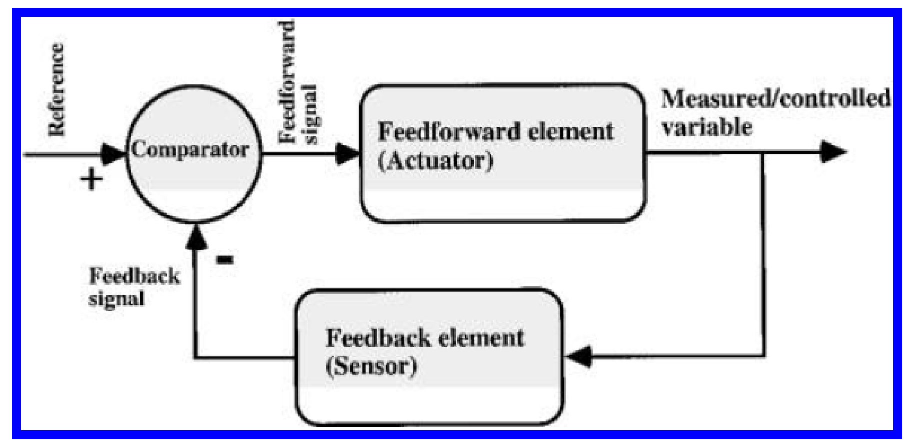




a) Predetermined, open-loop control

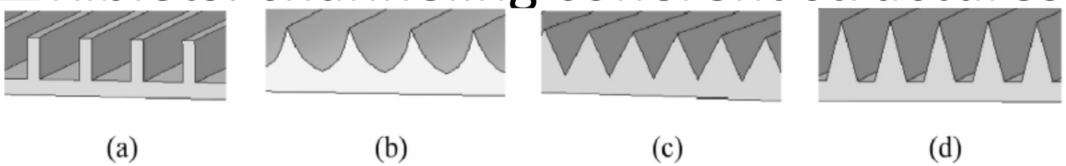


b) Reactive, feedforward, open-loop control



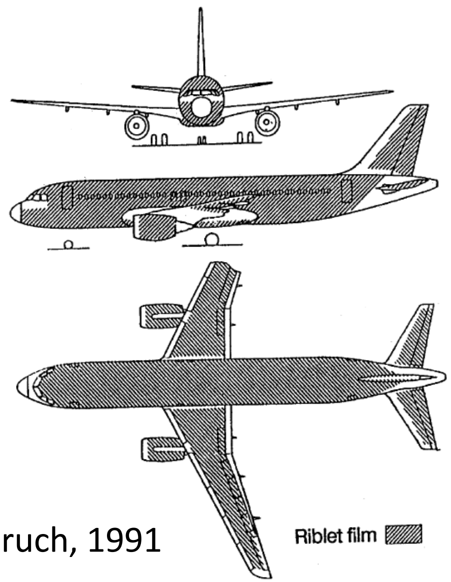
3. Friction management: example of passive control of TBL

- ❑ Riblets: channeling coherent structures



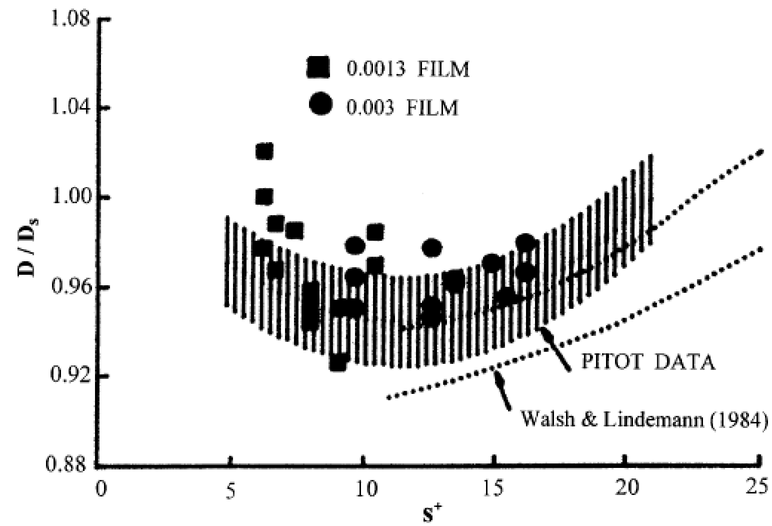
Soleimani, 2020

- ❑ For transonic conditions, typical depth of 100 microns



Szodruch, 1991

70% coverage, 2% drag reduction at cruise (Szodruch, 1991)

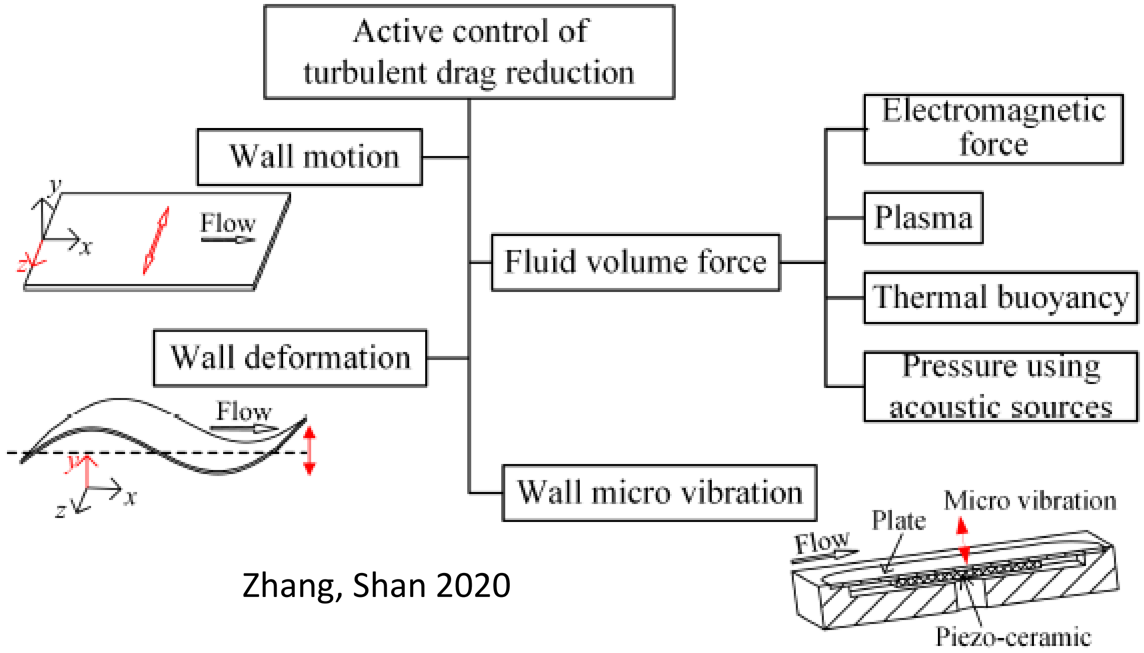


Walsh, 1988

- ❑ Although strong interest from film manufacturers, significant maintenance challenge (LH-LHT-RFT— Flight-tests with multi-functional coatings, EU-FP7 2011-2013)

3. Friction management: active control of TBL

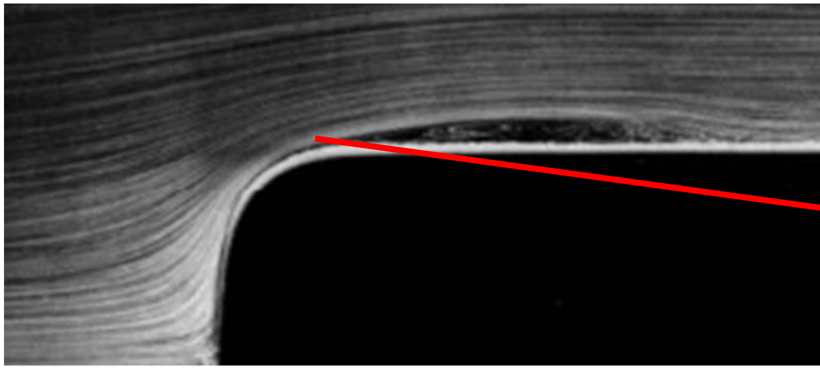
- ❑ General principle & some typical actuators

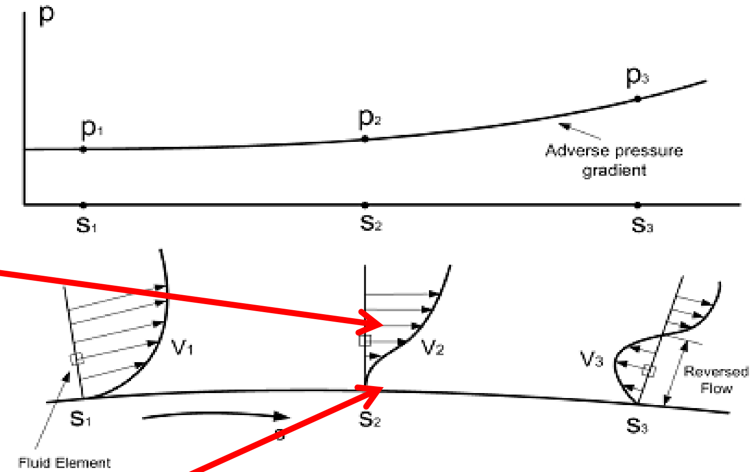


Zhang, Shan 2020

- ❑ General issue (research): a lack of systematic assessment of energy requirement and mass impact

4. Separation control: analysis of physics





Zero shear stress, $\tau_w = 0$

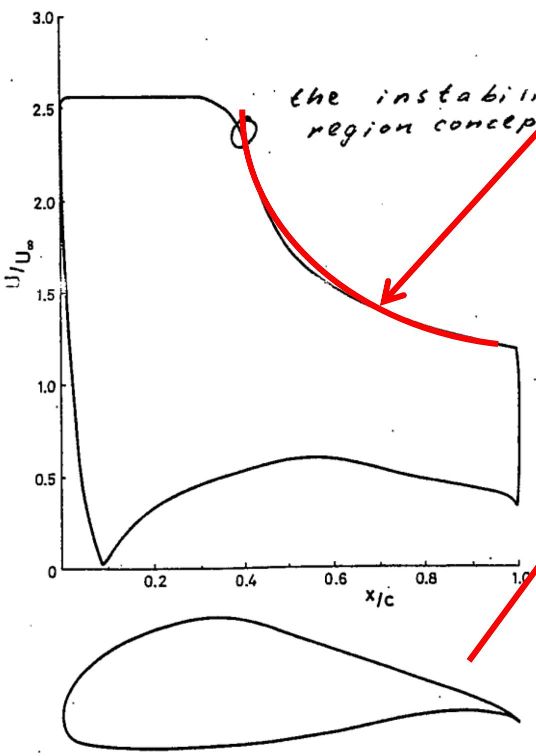
Therefore, the principle of separation control is always linked to:

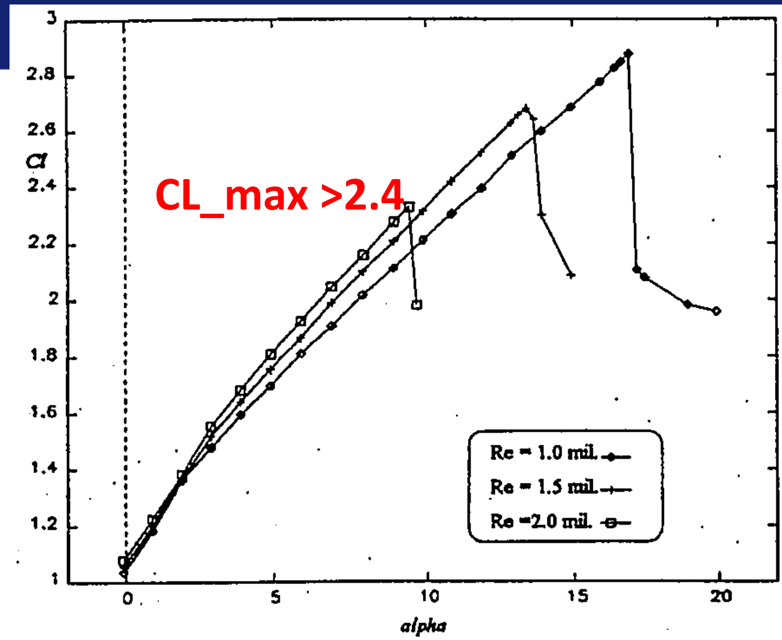
- ❑ Increase of momentum in the near-wall region: steady or cyclic/transient action

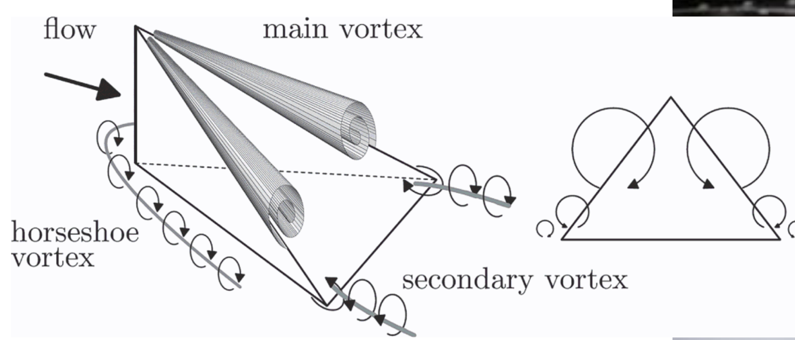
- ❑ Increase of mixing, usually through turbulence level

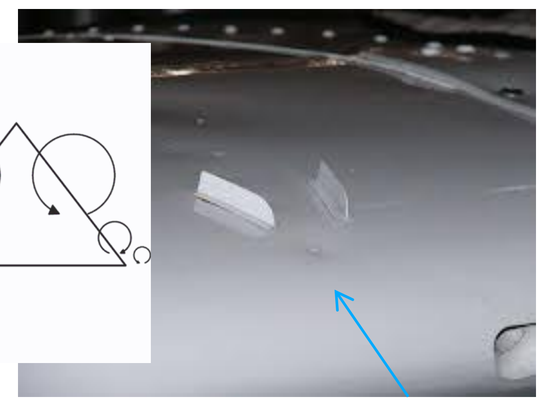
4. Separation control: examples of passive means

Optimal SHAPING of a high lift airfoil:
Based on Stratford pressure recovery



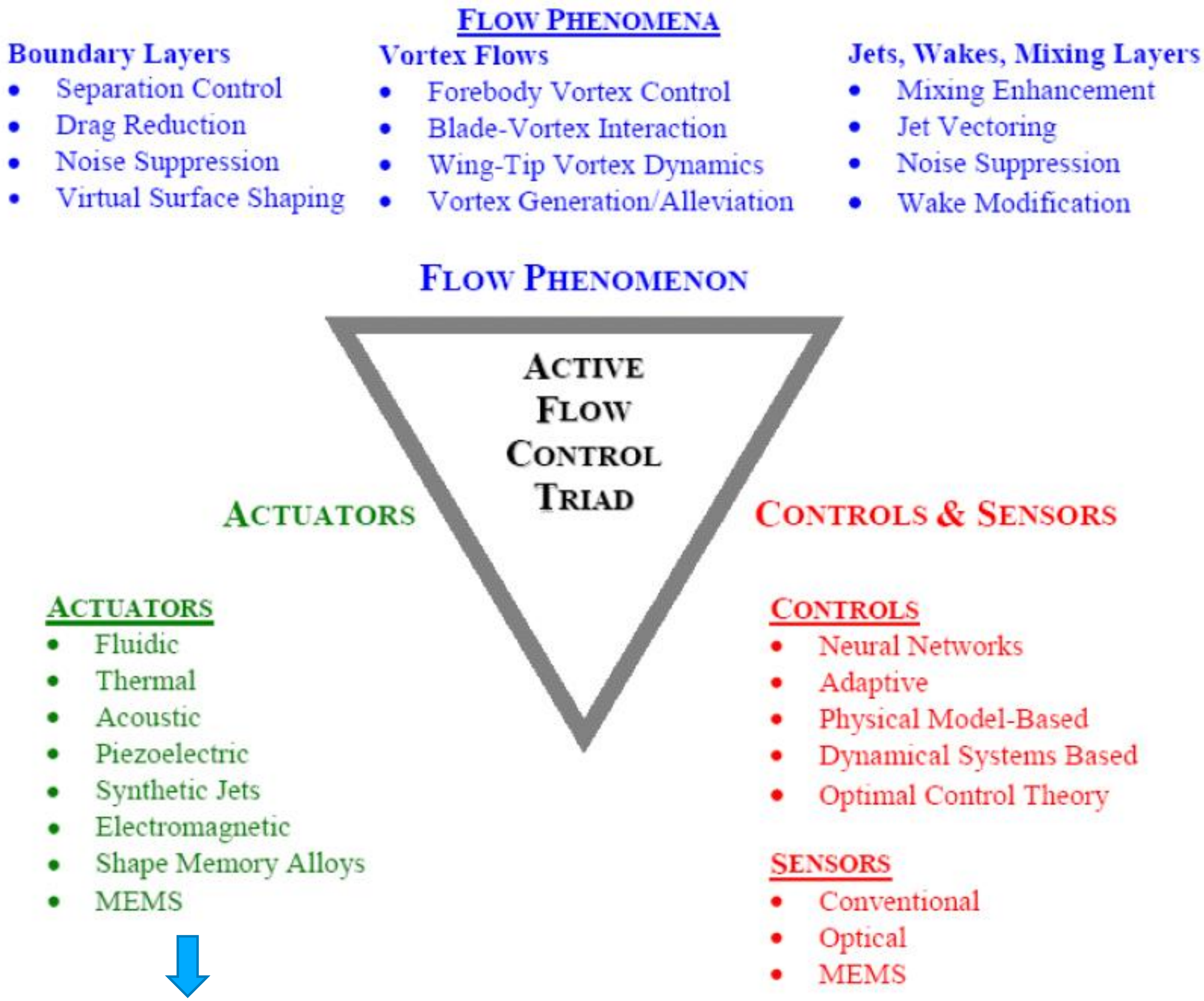






Increasing mixing of momentum: vortex generators
To be tuned to flow direction & boundary layer thickness

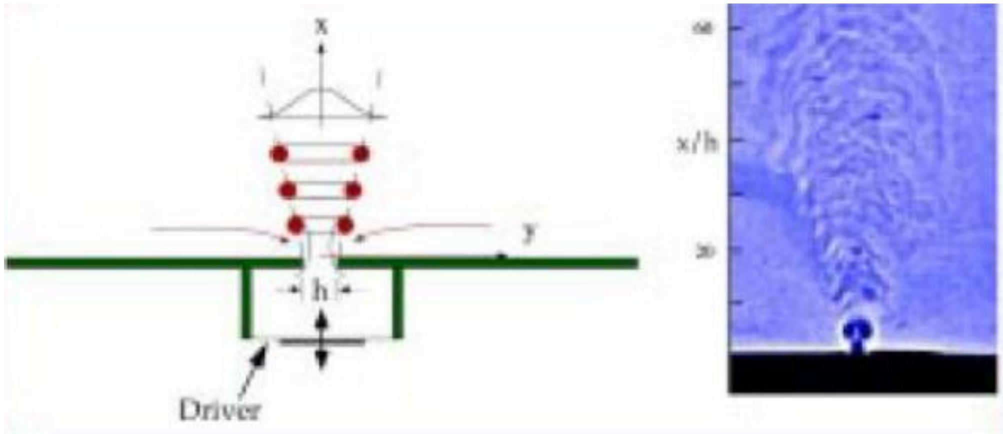
4. Separation control: review of active means



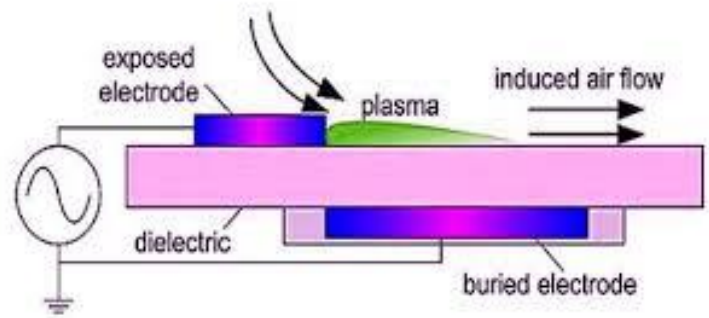
https://www.annualreviews.org/doi/abs/10.1146/annurev-fluid-122109-160634

Jahanmiri, 2010

4. Separation control: examples of active means



Synthetic jets: zero net mass actuator



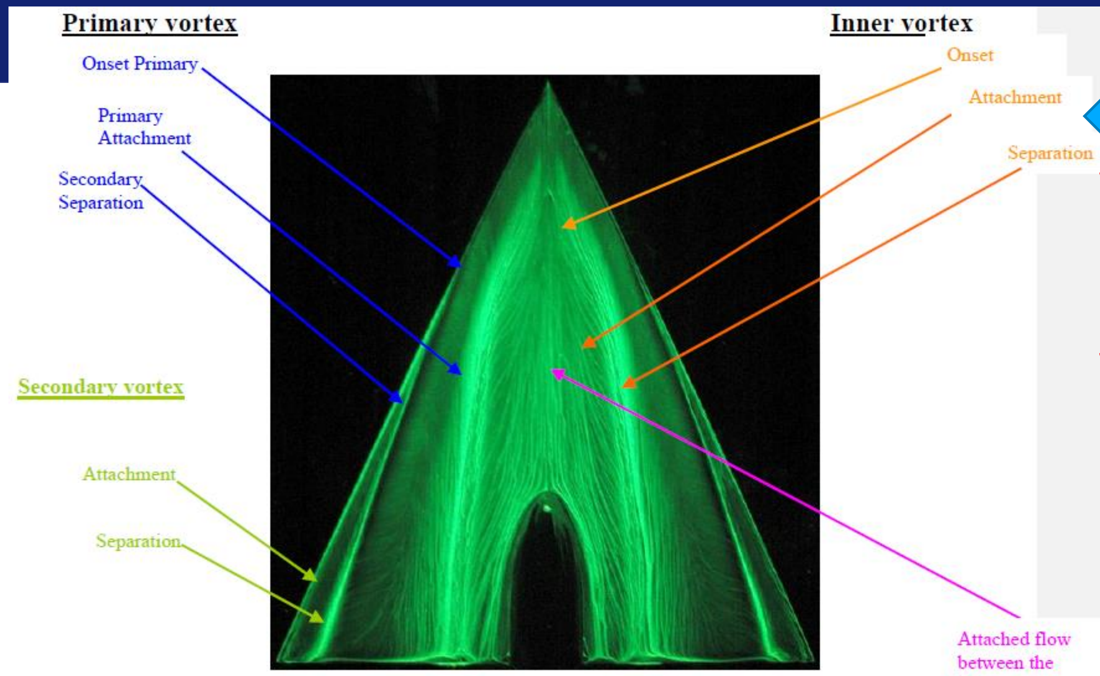
Plasma actuator: challenges to scale up in velocity. High voltage involved.

In all cases, the key issue are:

- ❑ technology maturity (TRL)
- ❑ system integration

$$\Delta M_F = \underbrace{\Delta M_S\left(e^{\frac{ctg}{f}}-1\right)}_{Mass} + \underbrace{\Delta D_S \frac{f}{g}\left(e^{\frac{ctg}{f}}-1\right)}_{Drag} + \underbrace{\frac{\kappa}{3600}\frac{\Delta P_S}{\eta_e}\frac{f}{cg}\left(e^{\frac{ctg}{f}}-1\right)}_{Electric}$$

4. Separation control: 3D challenges - applications

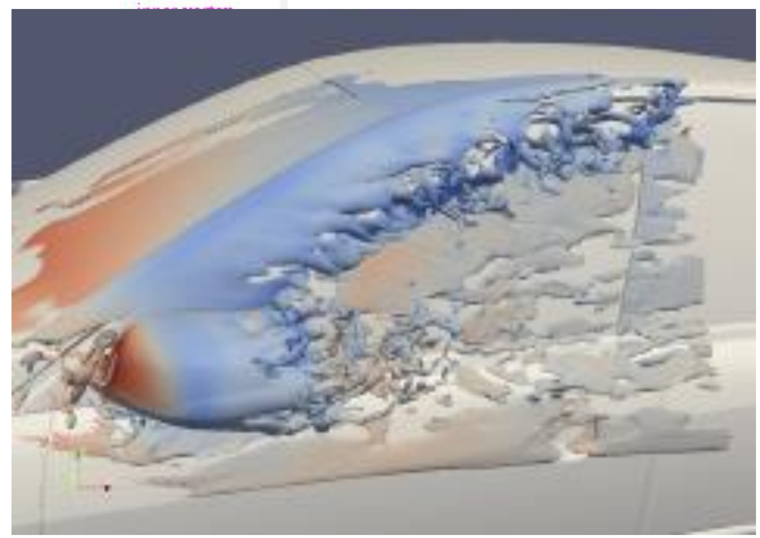


Vortex dominated flow & vortex induced lift: stall controlled by vortex burst

Boundary layer cross flow : 3D separation

Gand et al., POF 22 (115111),2010

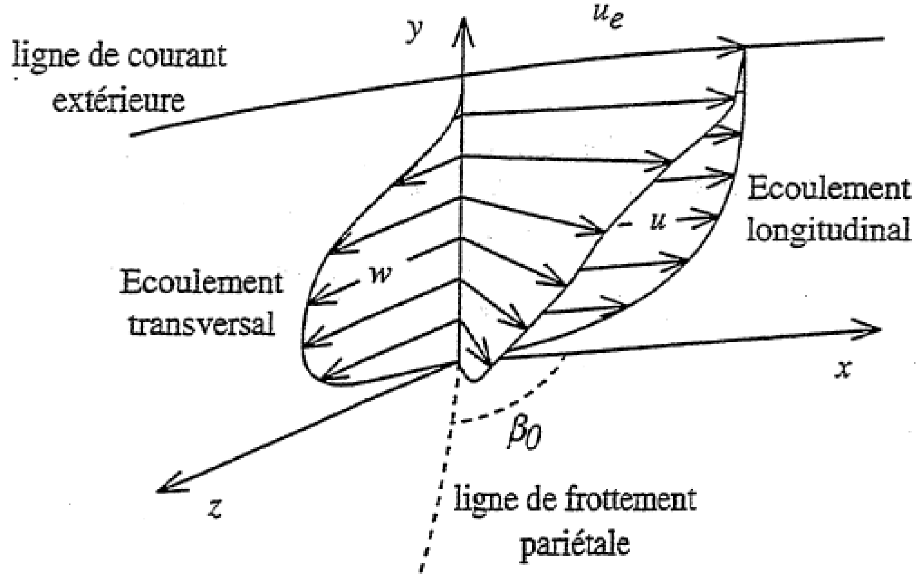
Bluff body separation



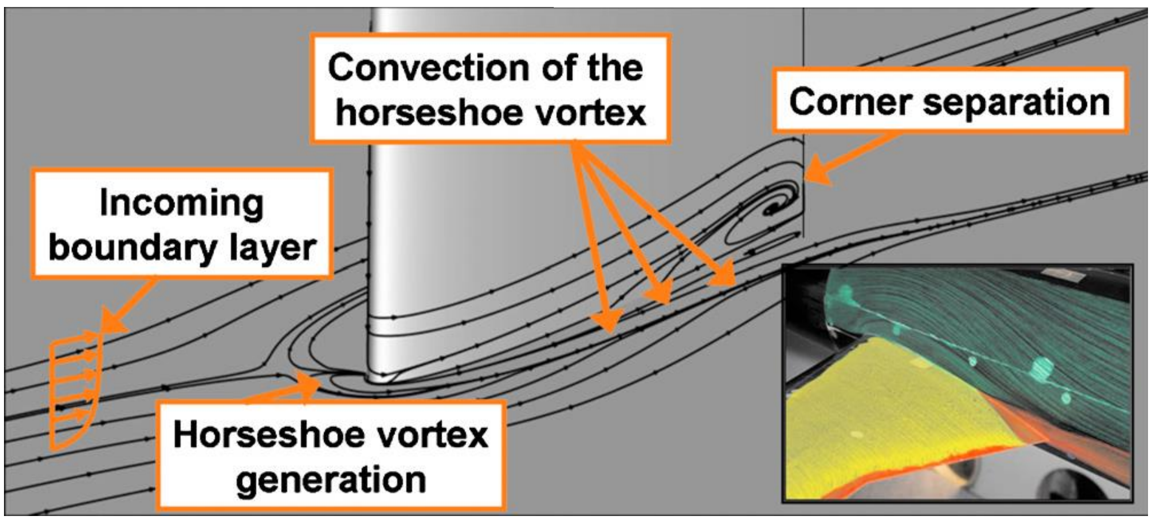
Guini, PhD Glasgow,2013

4. Separation control: 3D challenges - physics

Cross flow velocity composition

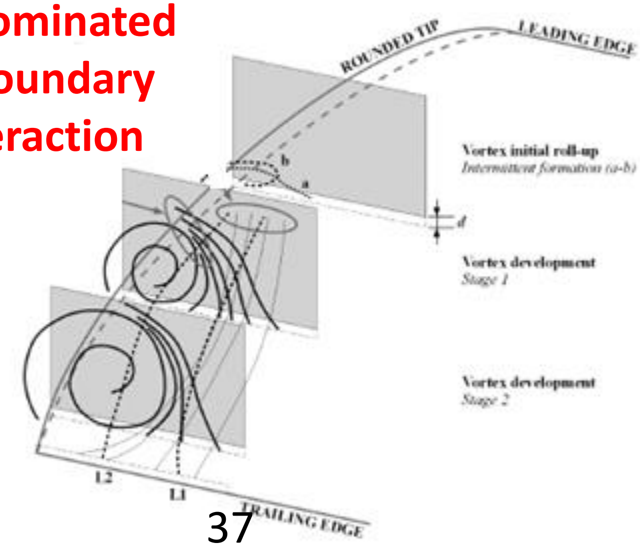


Guini,
PhD Glasgow U.,
2013



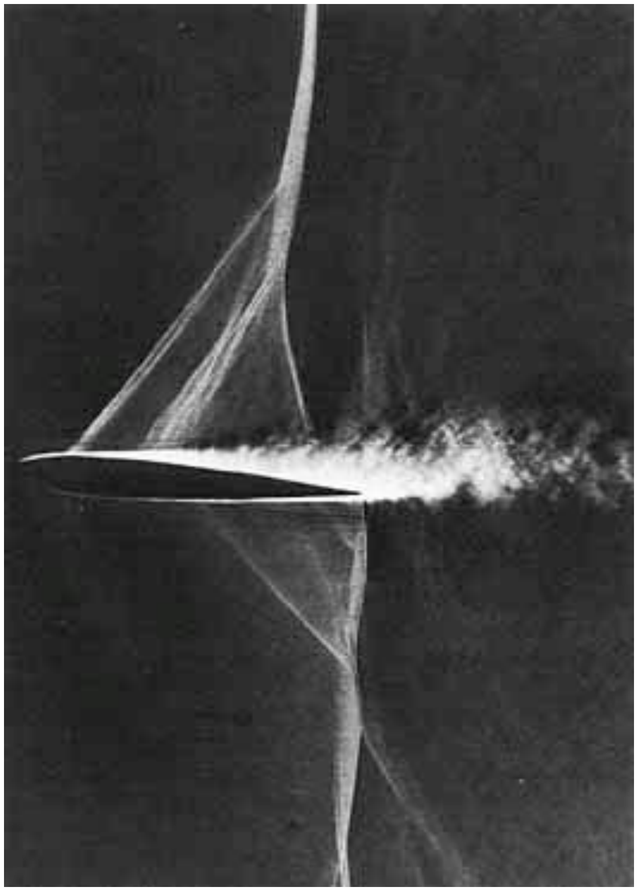
Gand et al., POF 22 (115111),2010

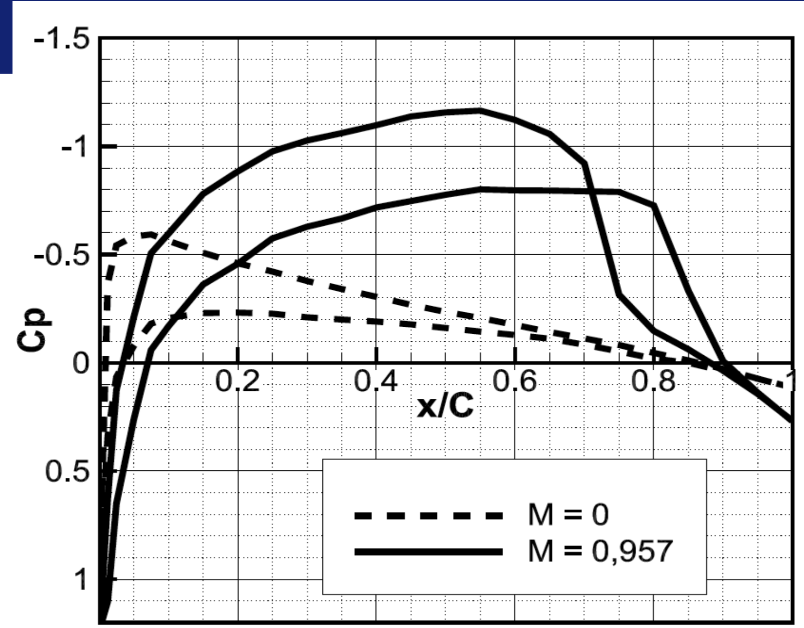
Vortex dominated flow & boundary layer interaction



5. Shock control: source of drag & unsteadiness (2D)

Strong shock wave – boundary layer

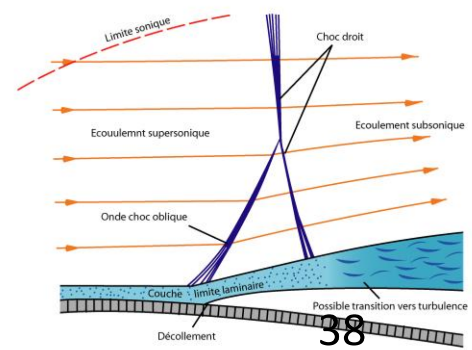




NACA 0012

$\alpha = 2°$

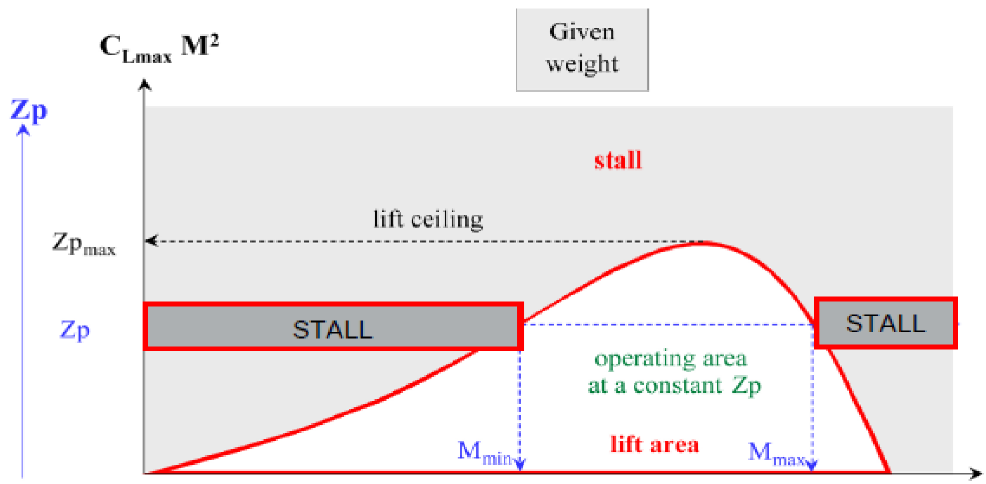
$M = 0{,}95$

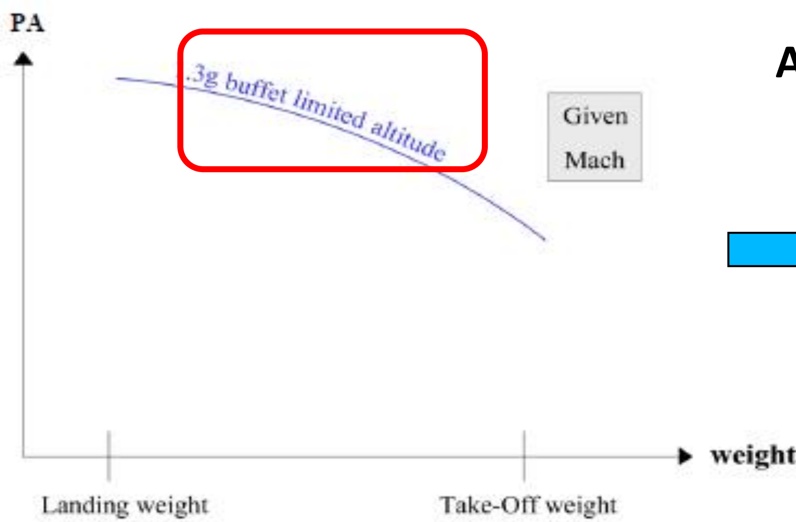


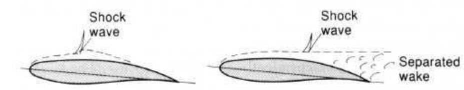
Leading to: drag divergence & buffet

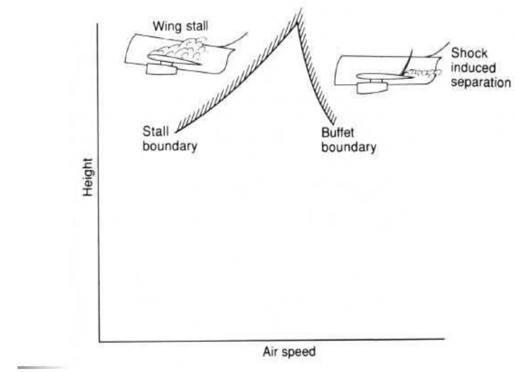
5. Shock control: stall & flight domain

At the lift limit, $n = \frac{0.7\, S\, P_S\, C_{Lmax}\, M^2}{m\, g}$









Airbus_Getting_to_Grips_With_Aircraft_Performance

A320

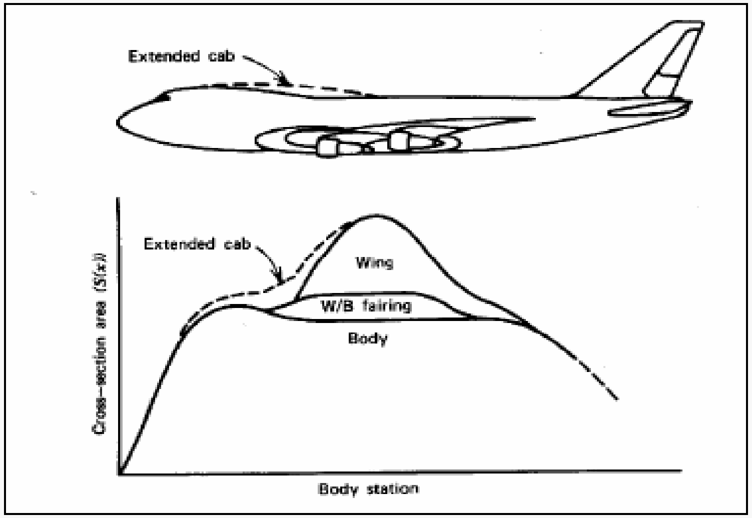
Assumptions:

n = 1.3
FL330
CG position: 31%
Weight: 70 t

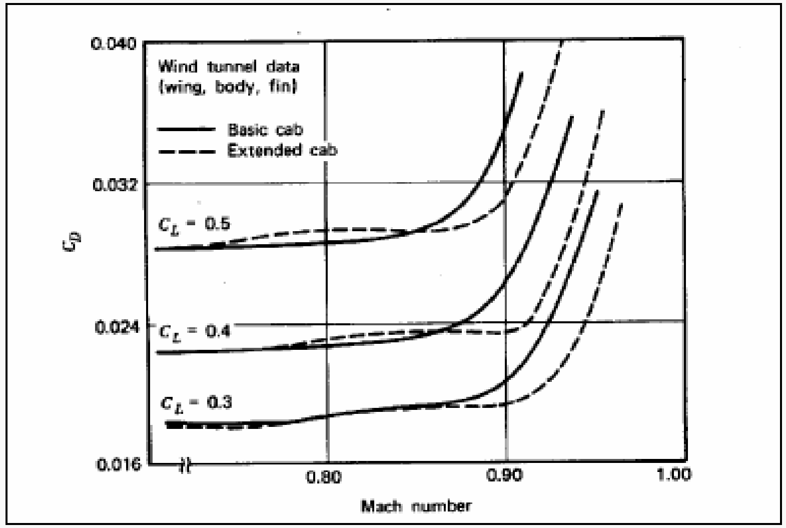
Results:

Speed range:
Mmin = M0.73
Mmax = M0.82

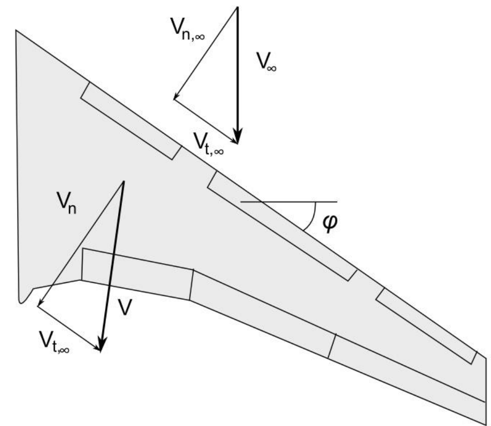
5. Shock control: passive means – shaping



Du Boeing 747-200 au Boeing 747-300



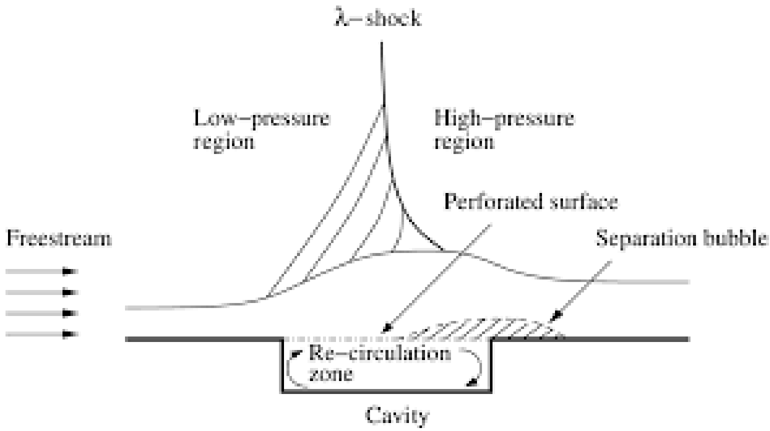
d'après Kuethe-Chow, Foundations of Aerodynamics

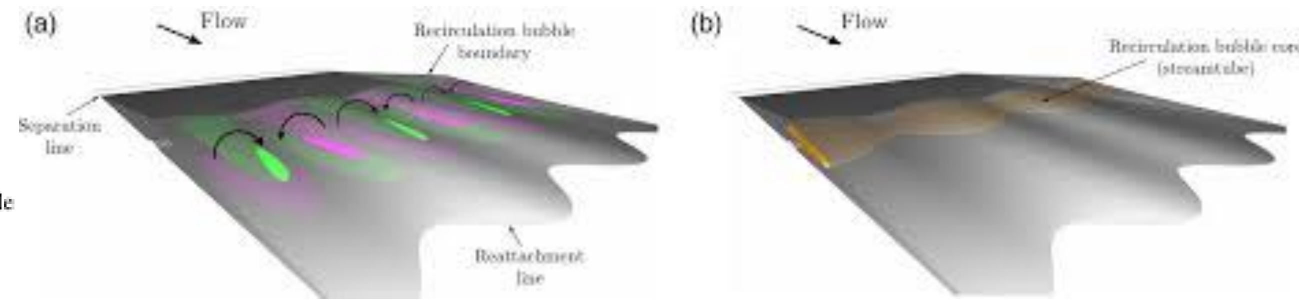


$$M_{critic}|_{aile} \approx M_{critic}|_{profil} \cos\phi$$

Design rule: progressive increase of frontal area
CFD methods have vastly improved the transonic design: the wave drag can be minimized to a minimum but remain the off-design cases…

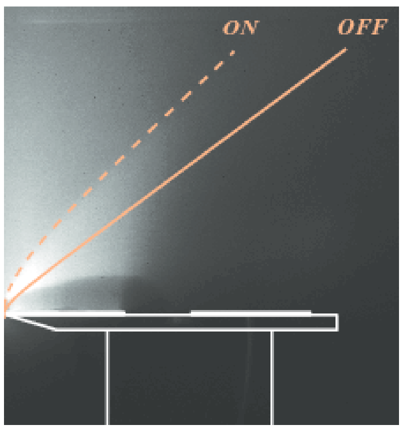
5. Shock control: passive means – BL flow control

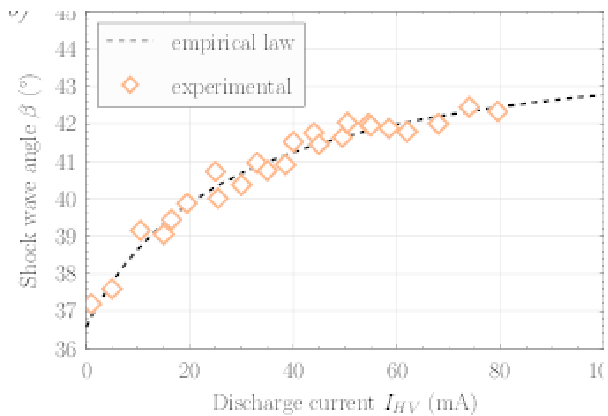




Flow over over porous wall: transfer of momentum through pressure inbalance

Vortex generator like process: 3D micro-ramps





… brute force can also be used: glow discharge…

6. Conclusion: key points

- Aerodynamics remains an overall design driven challenge!
- Requires a very specialist knowledge of aerodynamics & fluid mechanics
- Future aerodynamics is likely to be fully integrated with a large number of constraints: multidisciplinary!
- Although most of the key physical processes are known, fair representation of potential drag management /lift enhancement & interaction at aircraft level is a key issue
- Intrinsic linked to optimization
- Essential to evaluate the full chain of implications: TRL 0 to 10, including manufacuring & cost
- Reminder: typically 0.5 % L/D improvement each year (S. Bonnet’s lecture)

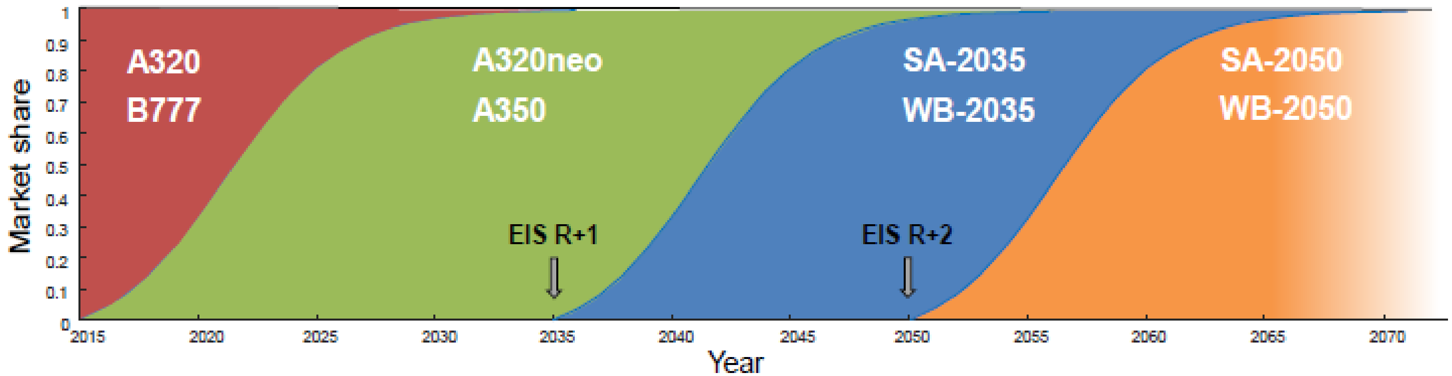
6. Conclusion: tables

Aerodynamics	Variable Camber	Retrofit	1 to 2%
	Riblets	Retrofit	1%
	Raked Wingtip	Retrofit	3 to 6%
	Winglets	Retrofit	3 to 6%

Aerodynamics	Natural Laminar Flow [27]	after 2020	8	5 to 10%
	Hybrid Laminar Flow [28]	after 2020	7	10 to 15%
	Variable Camber with New Control Surfaces [22]	after 2020	5	5 to 10%
	Spiroid Wingtip [22]	after 2020	7	2 to 6%

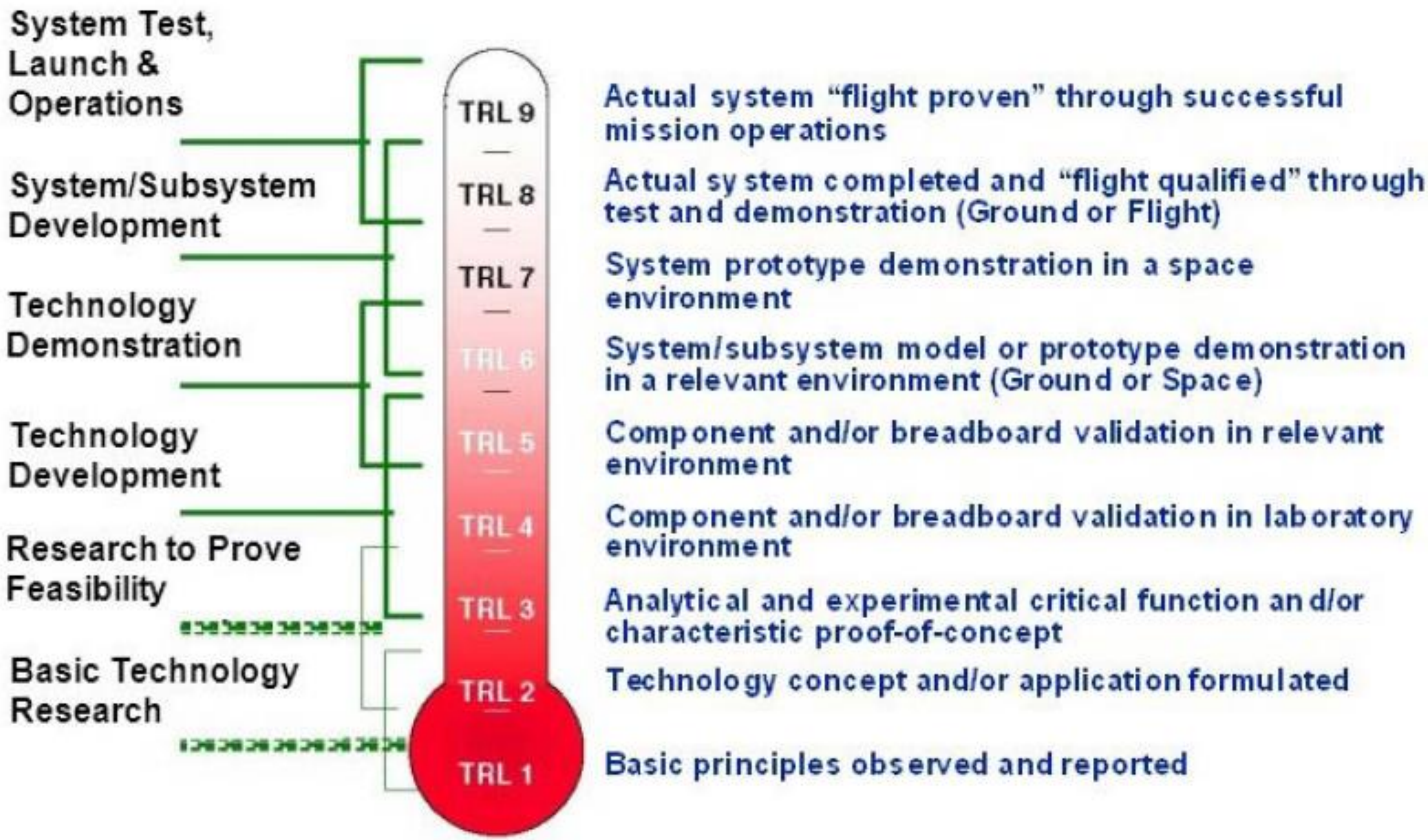
Aircraft Technology Roadmap to 2050 , IATA 2019

6. Conclusion: but remember (1)



Grewe et al (Nature Comm. 2021): Temporal evolution of the market share of aircraft segments. Typical +20 y of "propagation time" of a new aircraft/technology

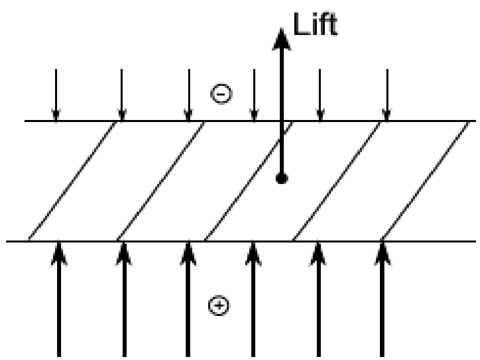
6. Conclusion: but remember - (2)
Technology Readiness Level

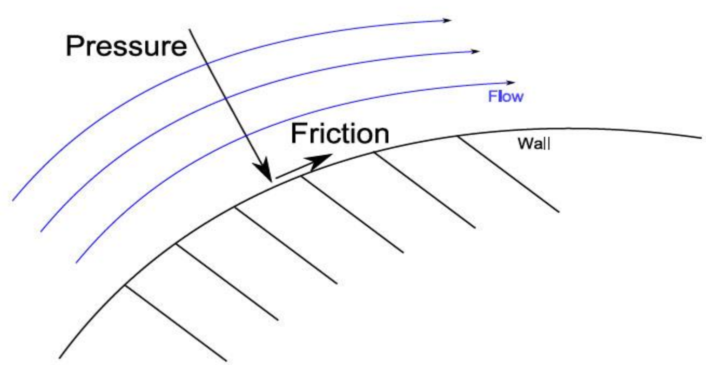


TYPICALLY, 2-3 YEARS TO JUMP OF 1 TRL

7. Complements (1): basic phenomena

2 basic interactions between fluid and a surface: pressure and shear stress

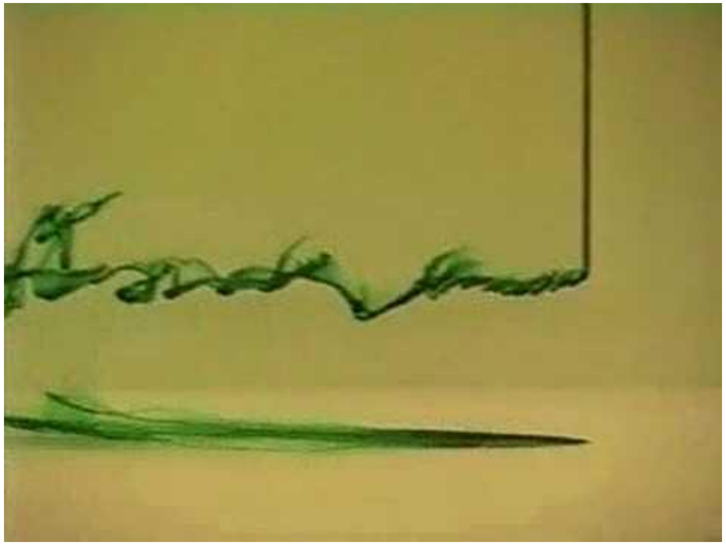


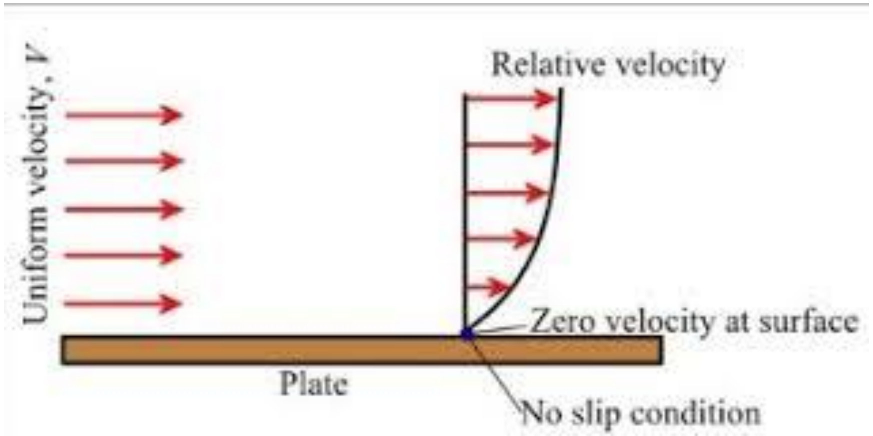


The basic scope of aerodynamics is the identification of the fluid forces everywhere on a given body to estimate the aerodynamic force.

7. Complements (2): friction

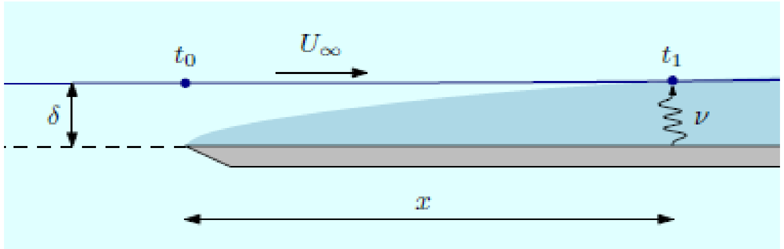
- Physical observation: the *non-slip condition,* **the fluid sticks to the surface**





- In regions of large velocity changes, *imposed by the non slip condition*, are comparatively thin w.r.t. a development length:

$$\boxed{\delta/_{L} \ll 1}$$



$$\boxed{\left[\frac{F_{inertia}}{F_{viscous}}\right] \propto \frac{U_\infty\, x}{\upsilon} \quad \textbf{= Reynolds number}}$$

7. Complements (3): Reynolds number

- Reynolds number hugely varies but usually takes a large value:
- Living world: Bee $Re \sim 10^3$, Vein $Re \sim 10^3$
- In aeronautics:

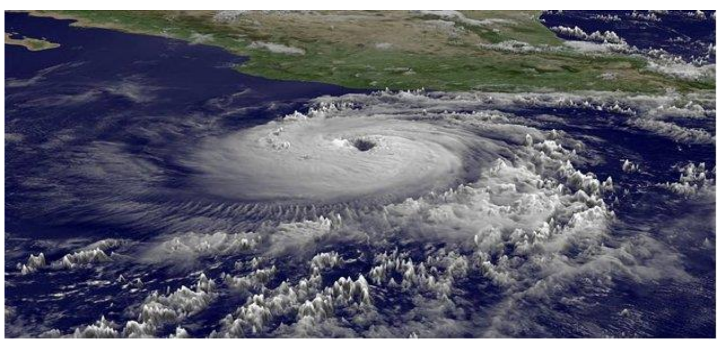
UAV: $Re = 10^3 - 10^6$

Gliders- Microlights – GA: $Re = 10^6 - 10^7$

Civil Aviation: $Re = 10^7 - 10^8$

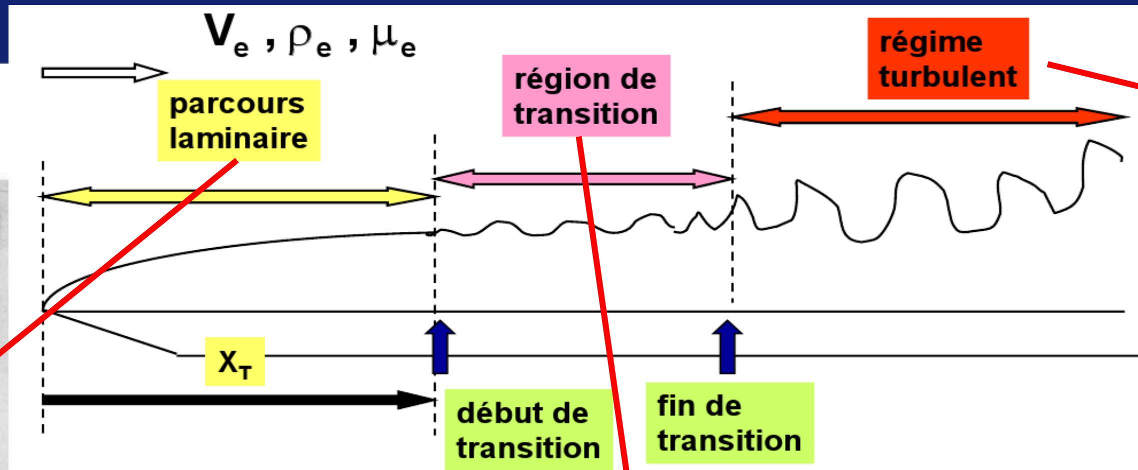
- In automotive industry: $Re = 3.10^6 - 3.10^7$

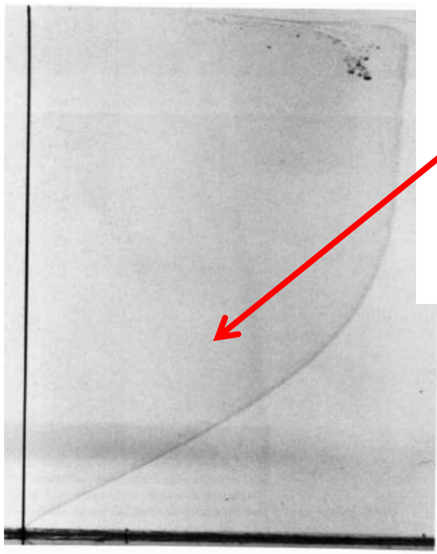
- Atmosphere:

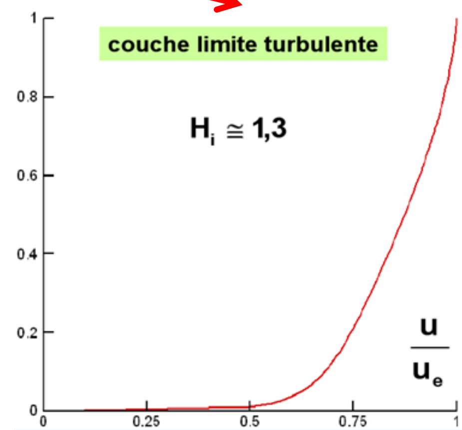


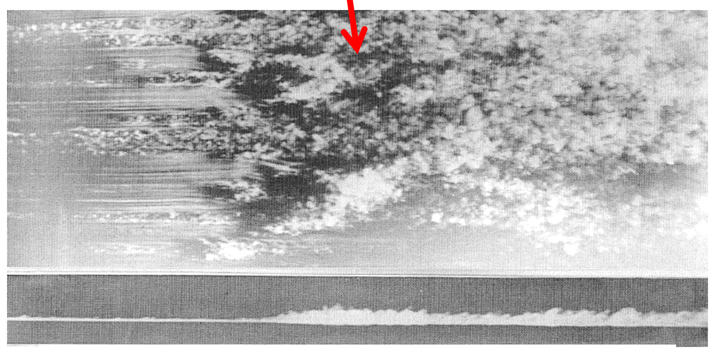
$Re = 10^8 - 10^{11}$?

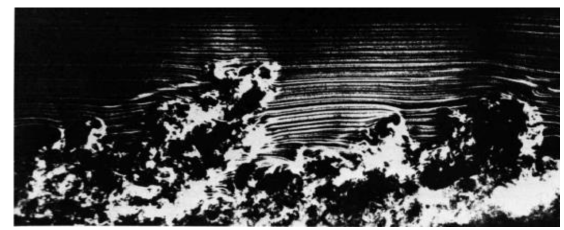
7. Complements (4): boundary layer (flat plate)

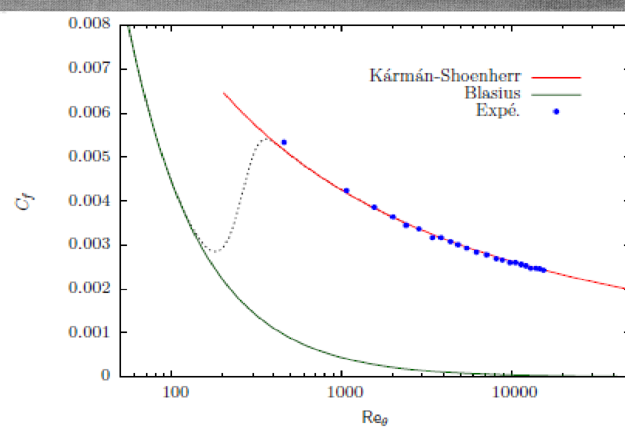












Laminar to turbulent transition:

○**Increase of skin friction**

○**Fonction of Reynolds number**;

○Dependent on surface quality, three-dimensionality, atmospheric environment

Many sides to turbulence…

○**Strong mixing**;

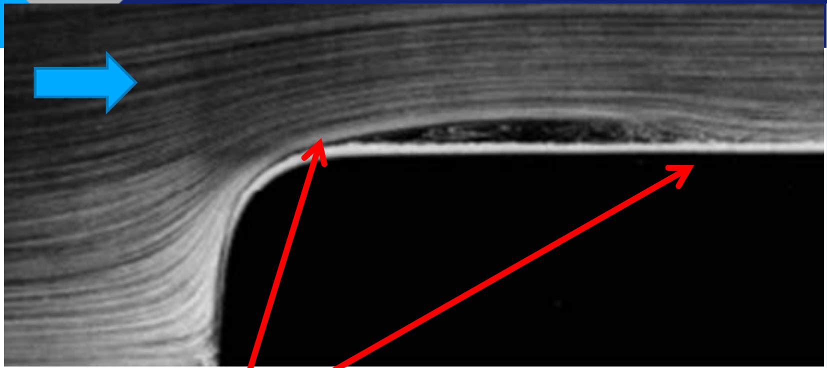
○All time and spatial scales involved;

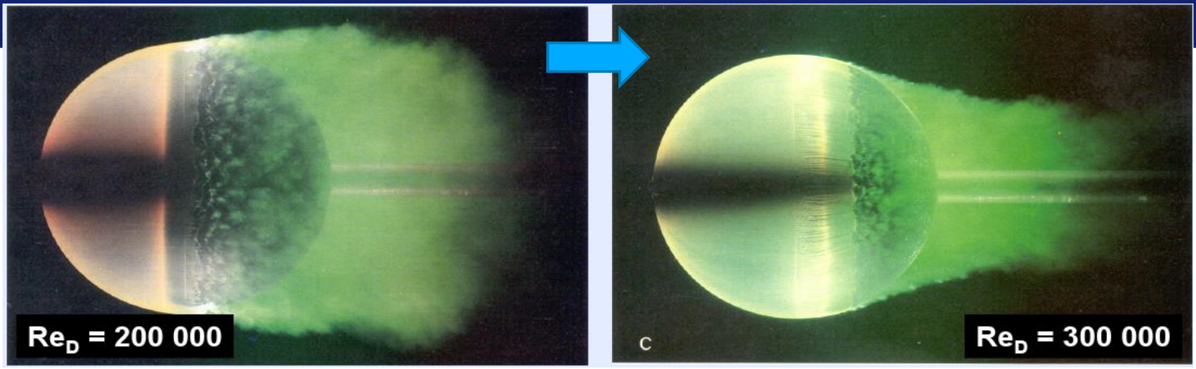
○Fully three-dimensional;

○Strongly time dependent;

○Dominated by vortices

7. Complements (5): from separation to stall



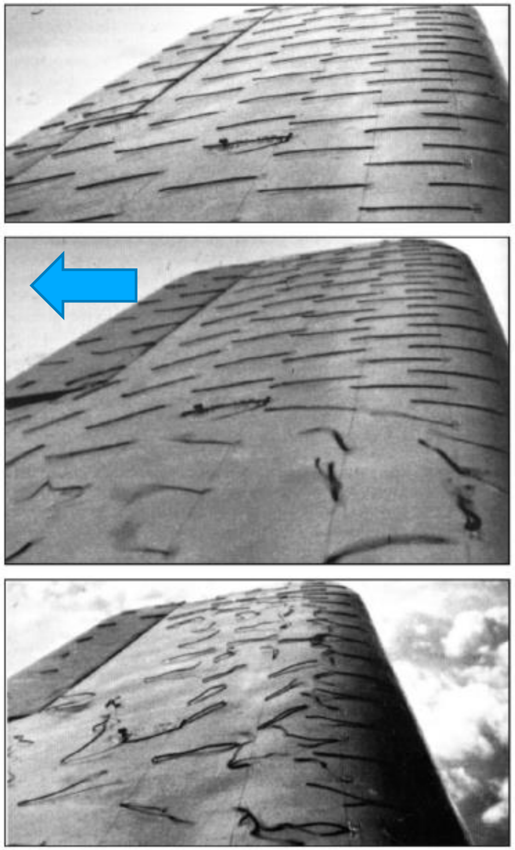


- Separation & reattachment:

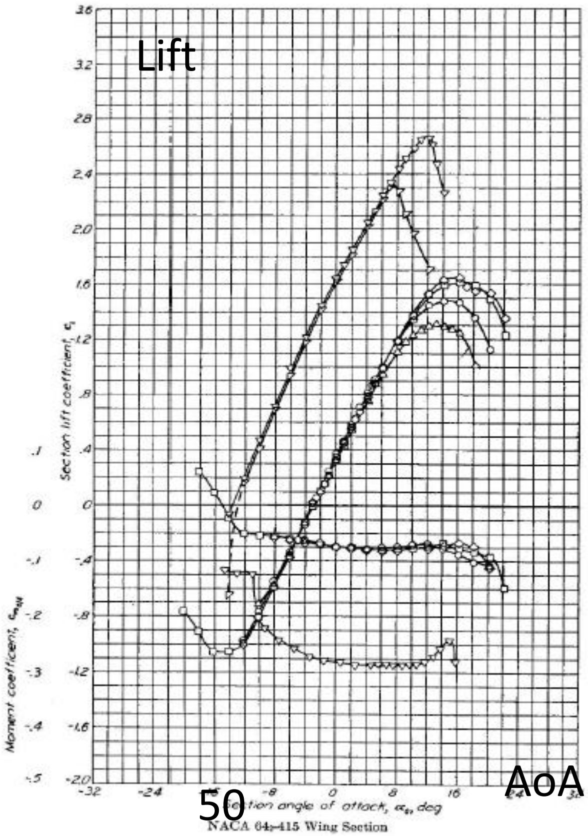
Zero shear stress

$\tau_w = 0$

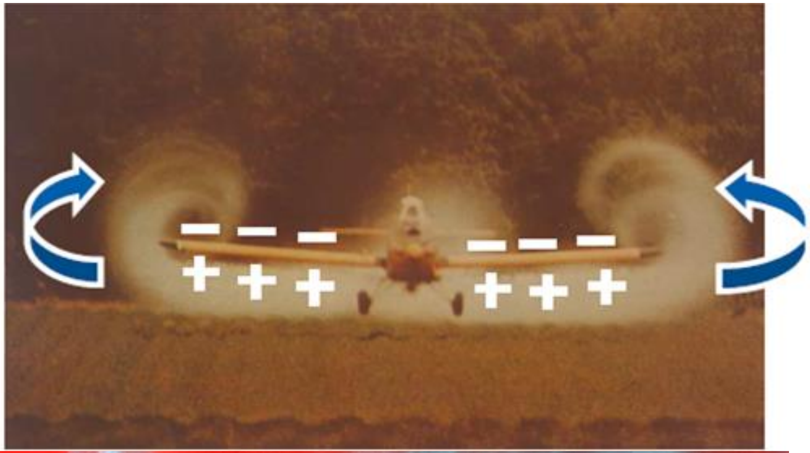
- The **stall** is a global – airfoil scale – form of **separation**
- Shape and angle of attack dependent
- Function of Reynolds

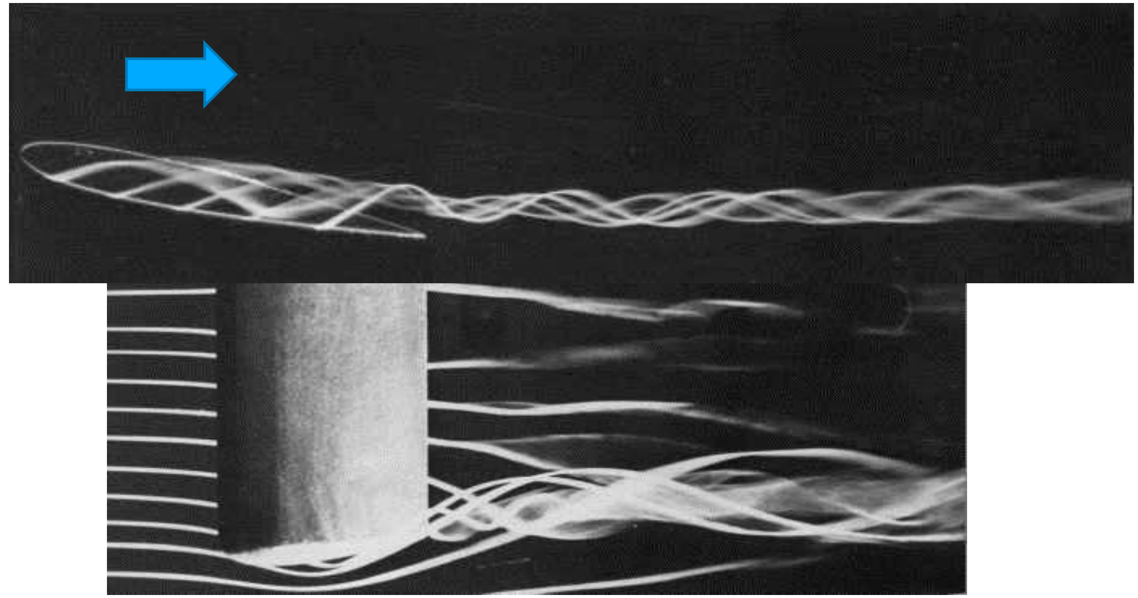


AoA ↗



7. Complements (6): 3D nature and vortices





Smoke visualization on rectangular wing, 24° AoA and $Re_c=10^5$

3D wing and edge effects

Non lift-dependent

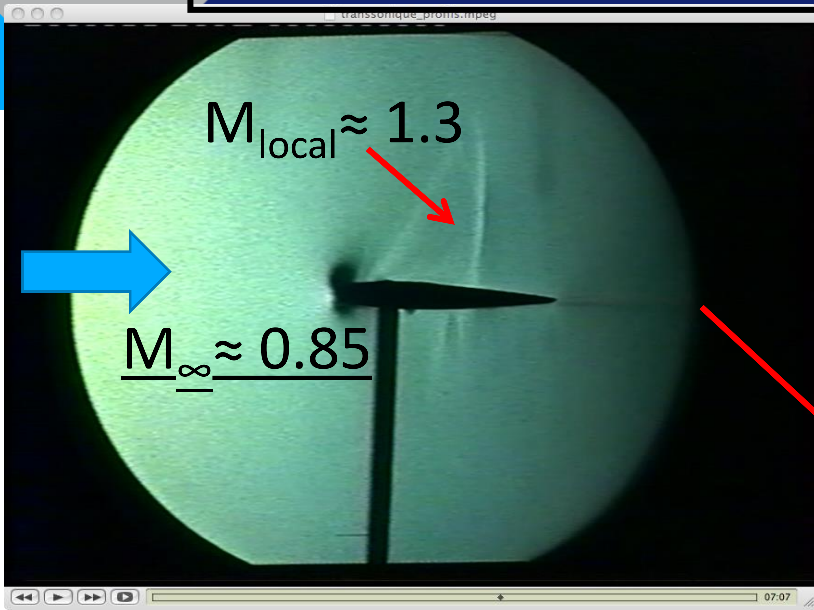
Lift-dependent

$$C_D \sim C_{D0} + \frac{Ki}{\pi AR} C_L^{\ 2}$$

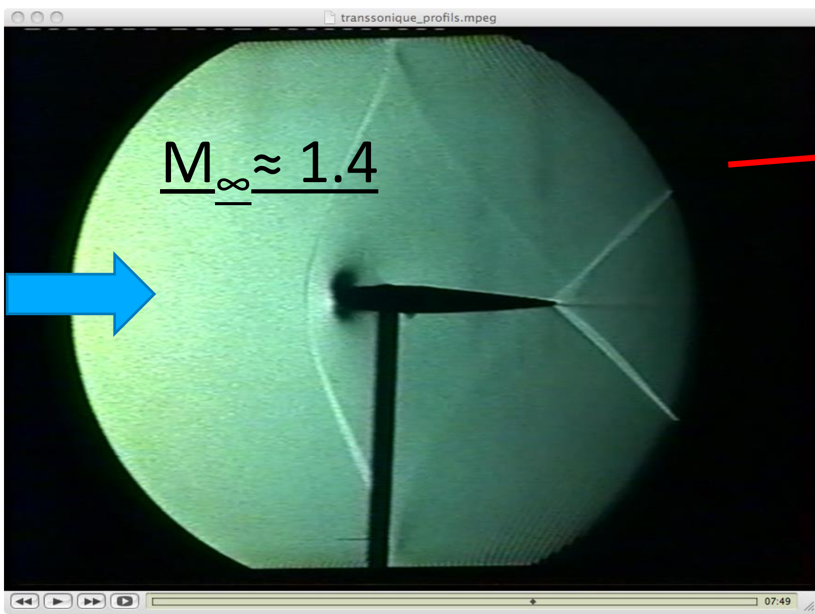
Aspect Ratio, $AR = b^2 / S_{REF}$

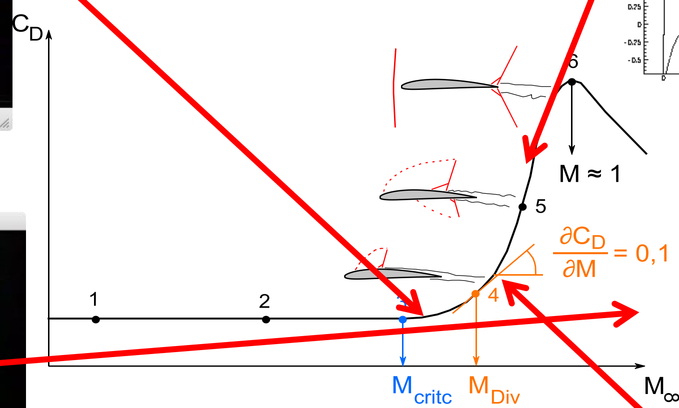
7. Complements (7): compressible flows

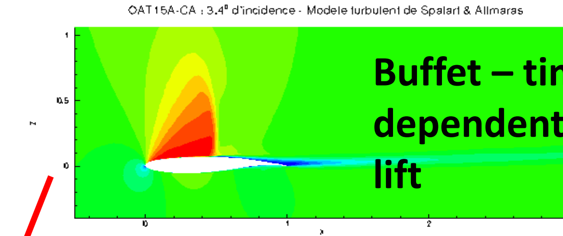
Strong shock wave



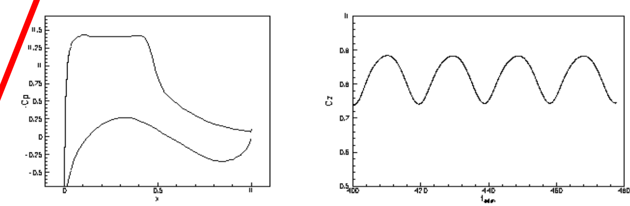
NACA 0012, $\alpha = 4°$

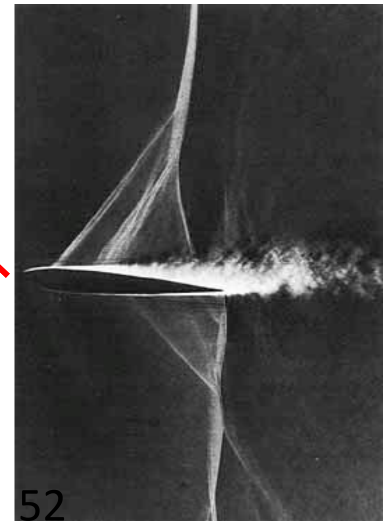






Buffet – time dependent lift





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