Numerical and experimental aerodynamics: validation and bias

J.-L. Hantrais-Gervois with the help of D. Destarac

***ONERA**, Applied Aerodynamics Department, Civil Aircraft Unit*

25th of May 2016 - AirTN-NextGen Workshop on Virtual testing, towards virtual certification

ONERA

THE FRENCH AEROSPACE LAB

return on innovation

Outline

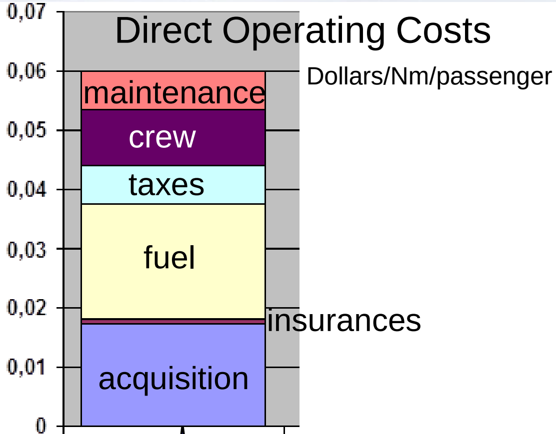
- Civil aircraft problematics
- Drag prediction: methods’ biases
    - Numerical methods RANS (CFD)
    - Experimental method in wind tunnel (EFD)
    - Experimental method in flight
- Numerical method validation
    - Examples of CFD / EFD and CFD / CFD comparisons
    - Accuracy of the numerical predictions
- Lessons learned about assessment in aerodynamics

Problematics

ONERA
THE FRENCH AEROSPACE LAB

Civil aircraft industry

- Purpose
  - Carry passengers or goods from A to B
  - Companies aim at
    - Either go as far as possible at the lowest cost
    - Or travel on short range at the lowest cost
  - Authorities require
    - To ensure safety
    - To reduce the emissions



- Fuel consumption is the main design driver

Bréguet-Leduc formula

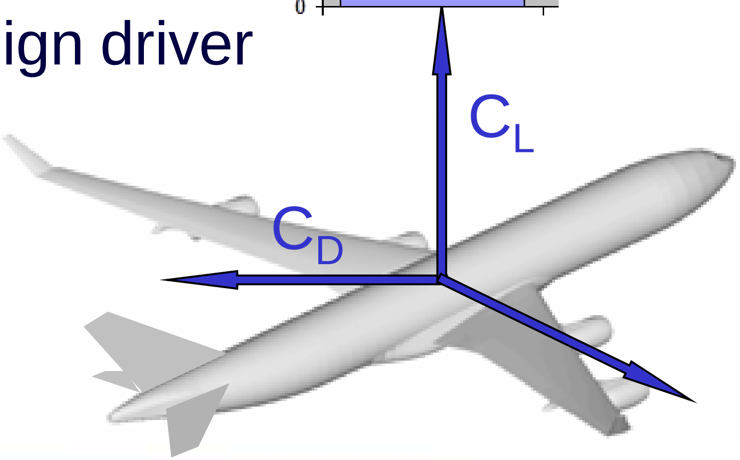
$$range \propto \frac{1}{consumption} \frac{MC_L}{C_D} \log\left(\frac{weight_{departure}}{weight_{arrival}}\right)$$

motorisation

aerodynamics

A380: C_D+1% ⇨ cost 1-2 t more fuel

structure

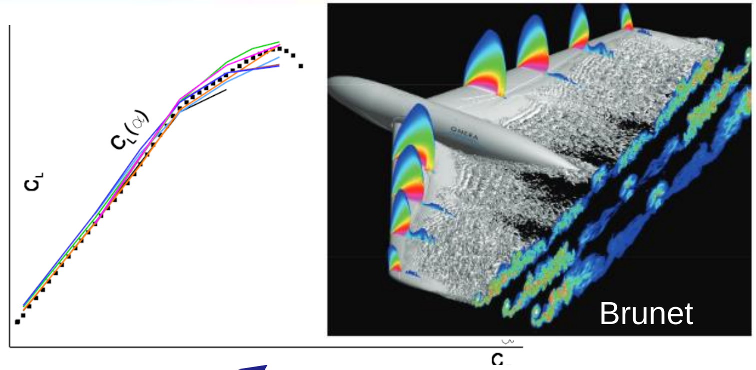


ONERA

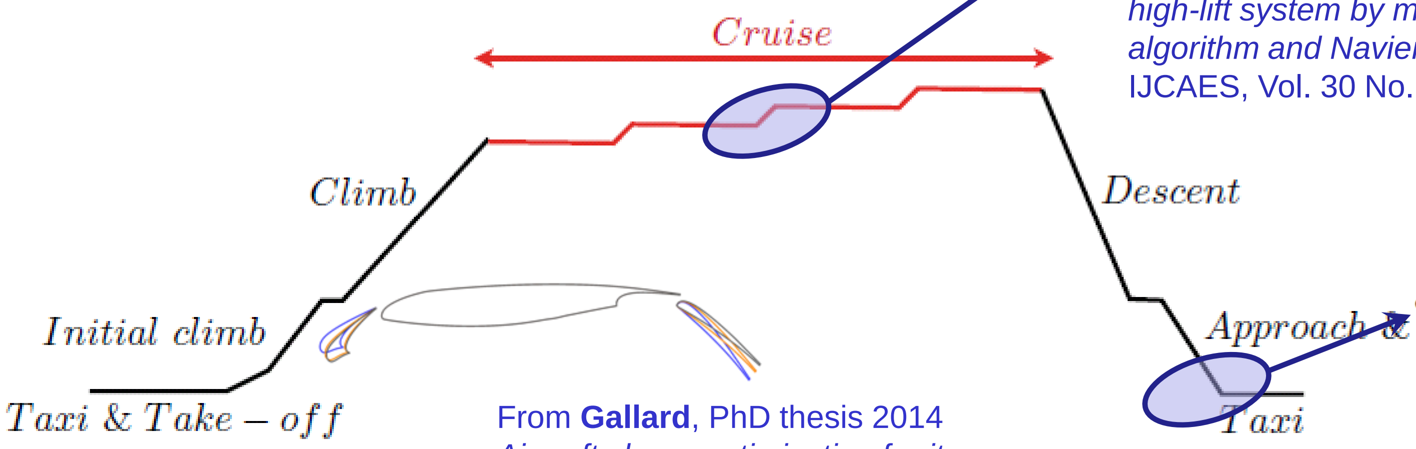
Civil aircraft certification topic

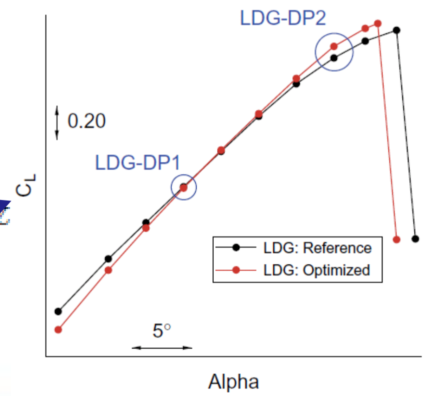
Hantrais-Gervois et al,
AG45 – Application of CFD to predict high g loads,
47th AAAF, March 2012

- Certification (flight part)
  - Cruise: no buffet in the flight domain
  - Low speed: flight domain limited by stall
    - Definition of the approach speed, runway length
    - Regulation requires minimum climb gradients under various conditions (engine failure)



Moens and Wervaecke
Multi-point optimization of shapes and settings of high-lift system by means of evolutionary algorithm and Navier-Stokes Equations
IJCAES, Vol. 30 No. 4, 2013, pp. 601-622



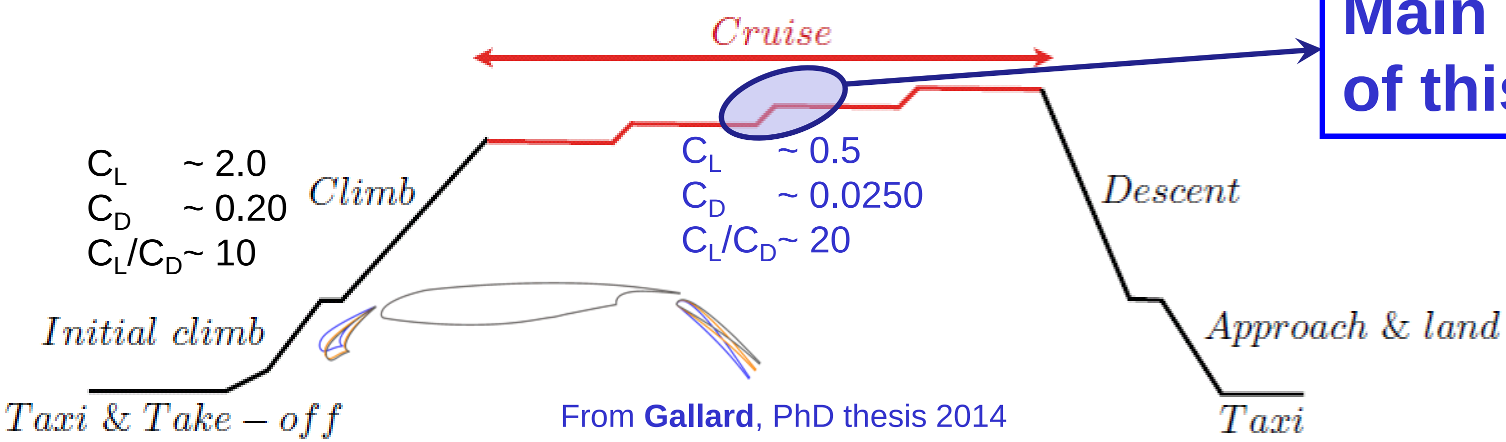


From **Gallard**, PhD thesis 2014
Aircraft shape optimisation for its overall mission performance

Civil aircraft efficiency topic

- Mission optimisation
  - Long range: cruise is the main segment to optimise
    - M x C_L/C_D or usually C_D
    - Clean wing
  - Short range: climb and descent are more important than cruise
    - Optimise climb C_{Lmax} and C_L/C_D
    - High lift wing

Main focus of this talk



From **Gallard**, PhD thesis 2014
Aircraft shape optimisation for its overall mission performance

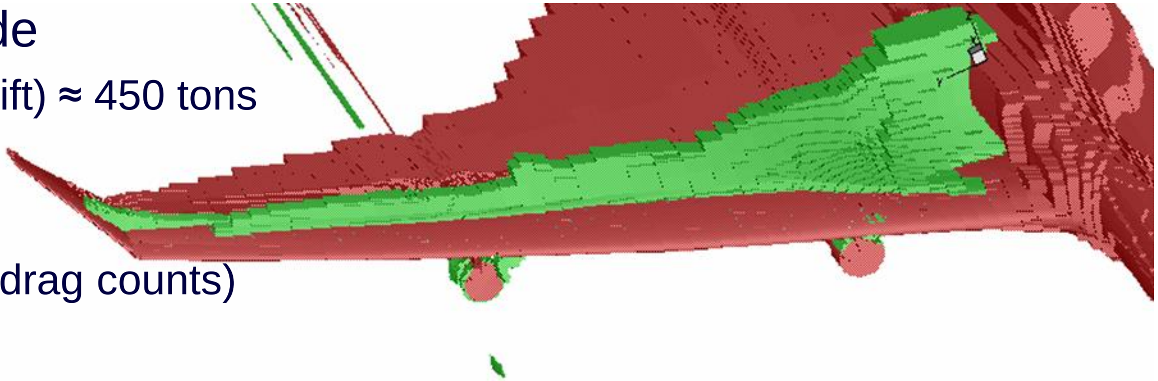
Figure 1.1: Typical civil transport aircraft mission profile.

ONERA

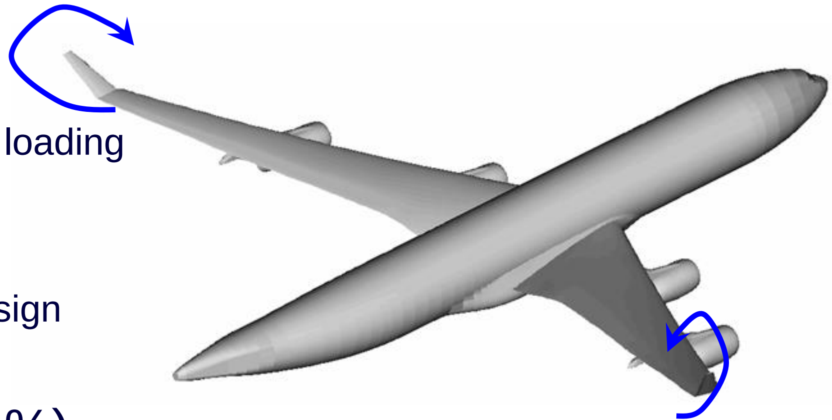
Cruise drag

Theory by van der Vooren and Destarac
Far-field / near-field drag balance and applications of drag extraction in CFD
Lecture Series CFD-Based Aircraft Drag Prediction and Reduction VKI, 2003

drag post-processing of a simulation



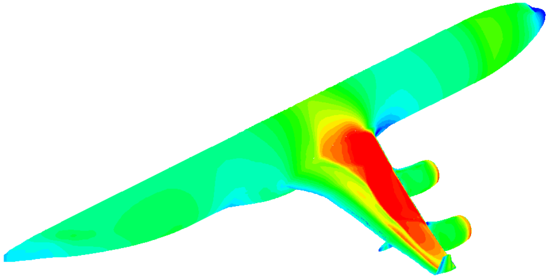
- A380 orders of magnitude
  - Cruise weight (and thus lift) ≈ 450 tons
  - Cruise drag ≈ 22 tons
  - $C_L \approx 0.50$
  - $C_D \approx 0.0250$ or 250 d.c. (drag counts)
- Physical drag sources
  - Viscous drag
    - ⇨ Linked to boundary layers ⇨ affected by wetted area, speed and altitude
    - ⇨ ~ 55% cruise drag
  - Lift induced drag
    - ⇨ linked to lift^2 ⇨ affected by wing span and loading
    - ⇨ ~ 40% cruise drag
  - Wave drag
    - ⇨ Linked to Mach number, lift and profile design
    - ⇨ ~ 5% cruise drag
- Accuracy goal = 1 drag count (~ 0.4%)



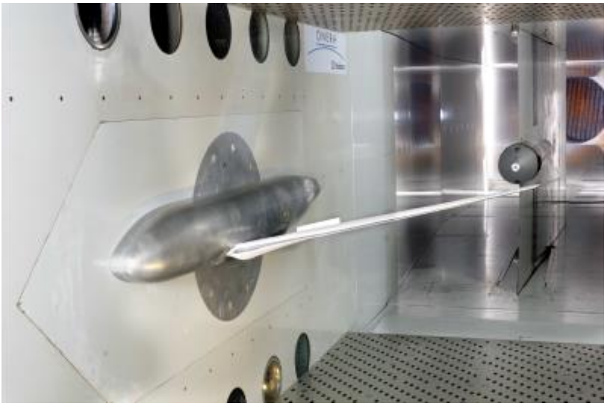
Drag prediction: methods' biases

Drag prediction

- Numerical method (CFD)
  - All along the elaboration process
  - Relatively cheap

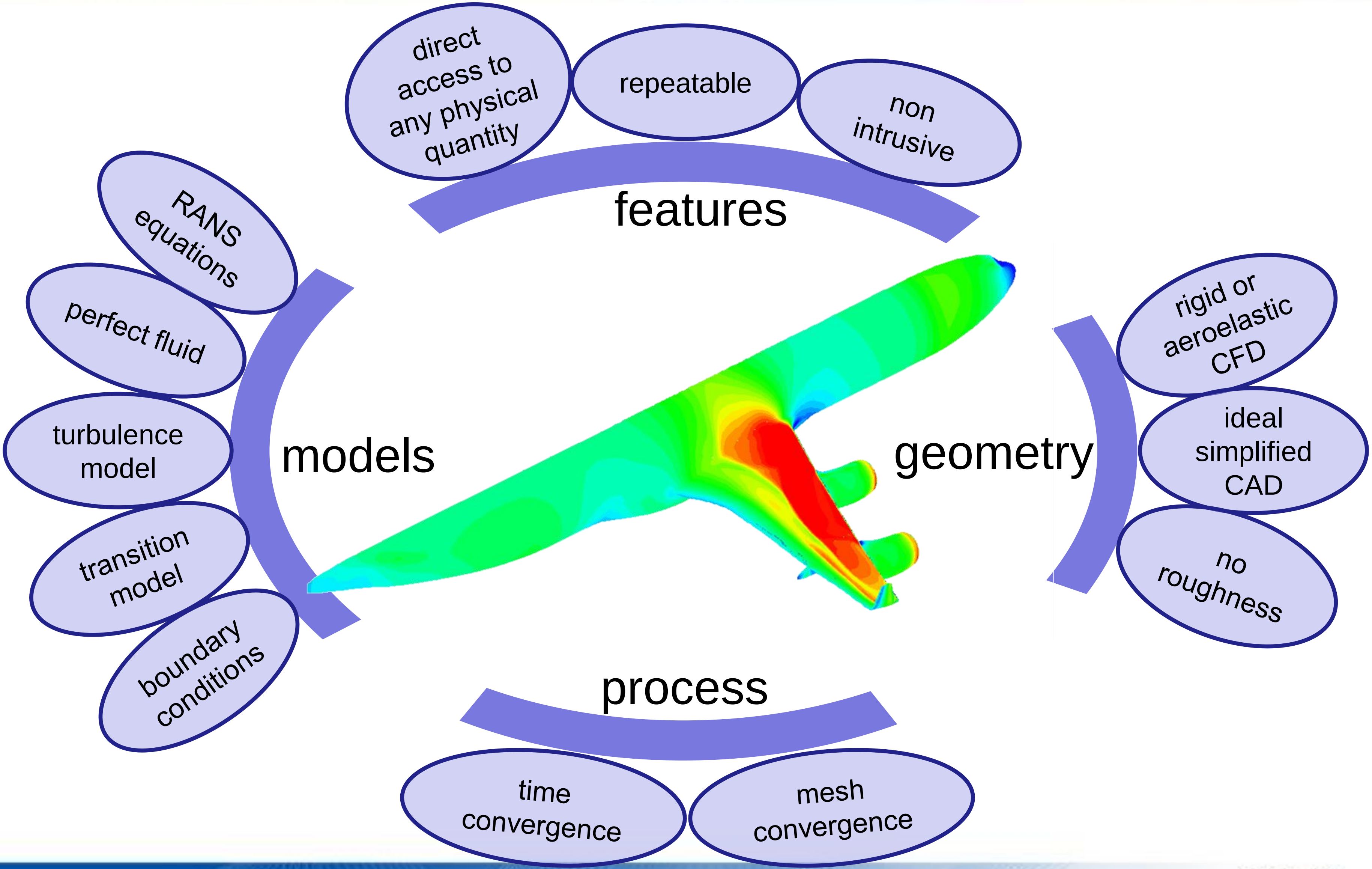


- Wind tunnel tests (EFD)
  - Validation of design choices
  - All the more late in the design process



- Flight tests
  - Expensive
  - At the end of the development process (certification)

CFD features



EFD features

features

repeatability checks…

local intrusive indirect measure

models

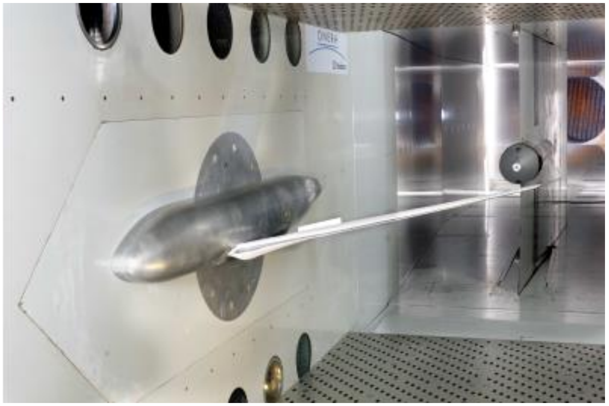
real fluid

high turbulence level

transition tripping

mounting effects

low Reynolds number



geometry

too rigid model

ideal simplified CAD

polishing

paint for measure

milling tolerance

process

continuous traverse

ONERA

flight tests features

features

hardly repeatable weather, pilot, loading

local intrusive indirect measure

models

real fluid

geometry

deform. with fuel loading

real with bolts & joins

process

measure on 30s level ground

ONERA

CFD mesh convergence

- Discretisation error needs to be coped with though a proper mesh convergence analysis
  - Richardson extrapolation
  - Great for 2D

Vassberg & Jameson
In Pursuit of Grid Convergence for Two-Dimensional Euler Solutions, Journal of Aircraft, 2010, vol. 47, 1152-1166

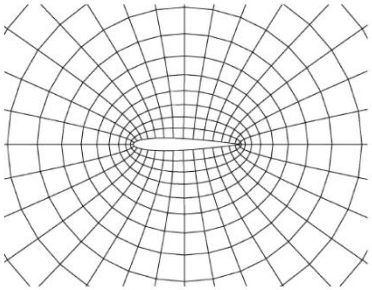


Fig. 3 Closeup of the 32 x 32 O-mesh.

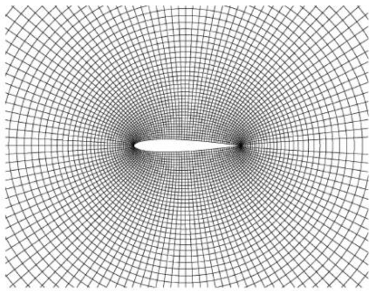


Fig. 5 Closeup of the 128 x 128 O-mesh.

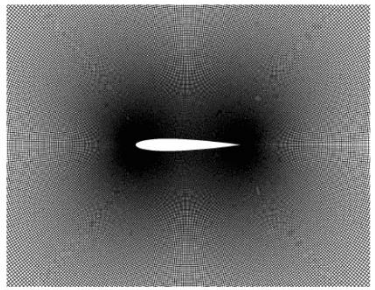
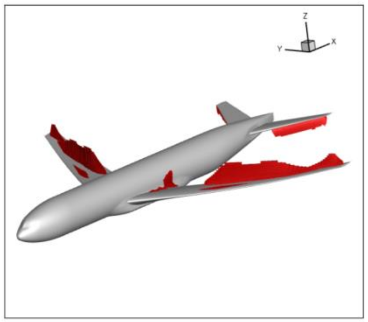
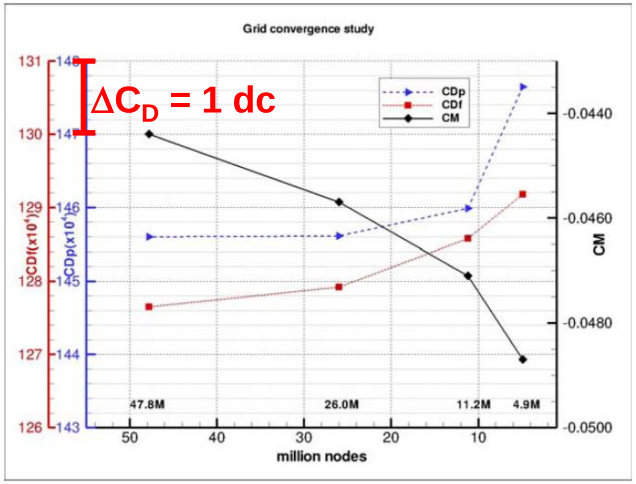


Fig. 7 Closeup of the 512 x 512 O-mesh.

- Difficult to apply in 3D
  - Meshes too consequent
  - Convergence order dependent on the coefficient



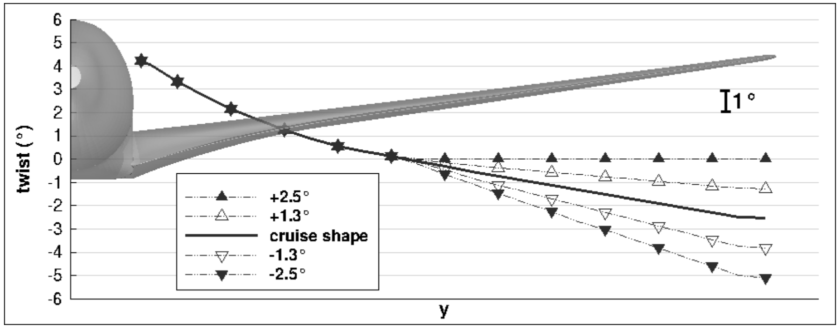


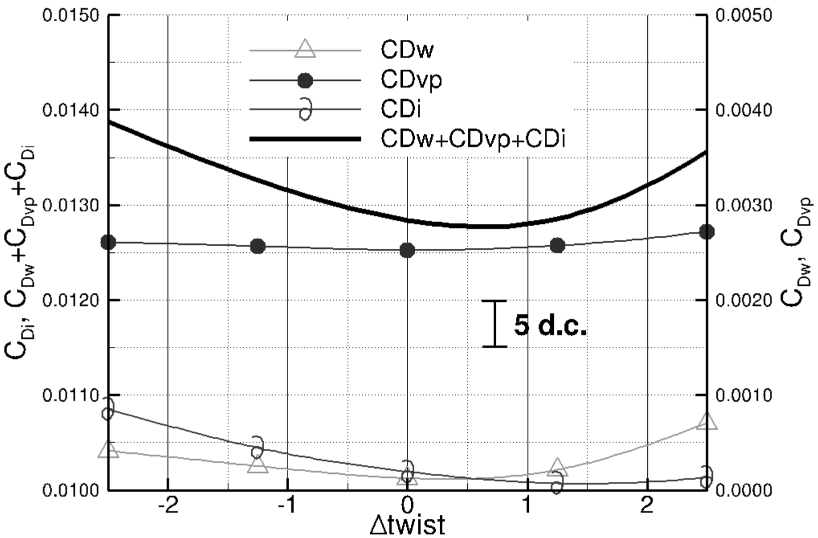
Hue, Esquieu, Gazaix
Computational drag and moment prediction of the DPW4 configuration using the elsA software
28th AIAA Applied Aerodynamics Conference, 2010

ONERA

Wing deformations

- Large effects of wing deformation
  - Mainly due to twist
- Flight shapes
  - One different shape for each
    - Weight, altitude, fuel position…
- Shapes in wind tunnel
  - Scale effect
  - Model more rigid than real aircraft
    - One single flight shape is achieved
- CFD
  - Can be rigid
  - More and more flexible





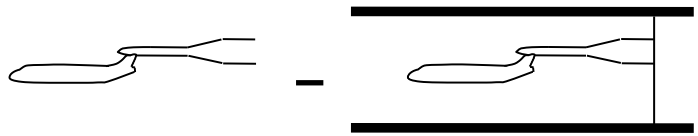
Hantrais-Gervois & Destarac
Drag Polar Invariance with Flexibility
Journal of Aircraft, Vol. 52, No.3, May-June 2015

ONERA

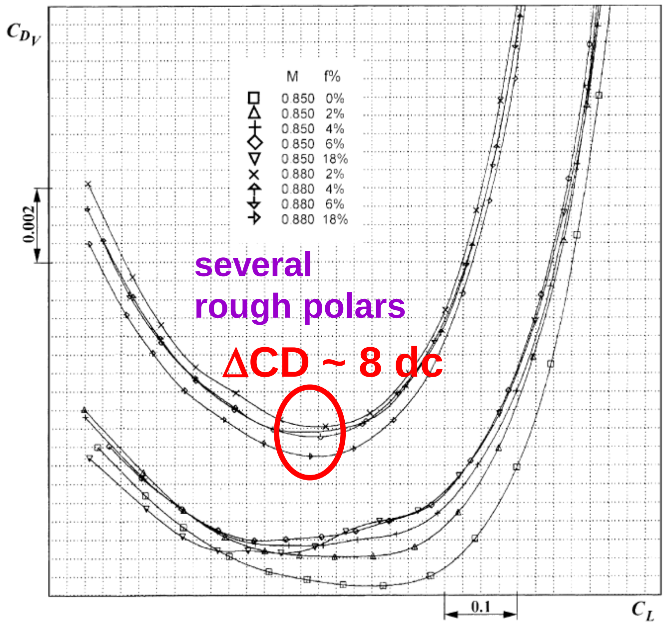
EFD wall interference

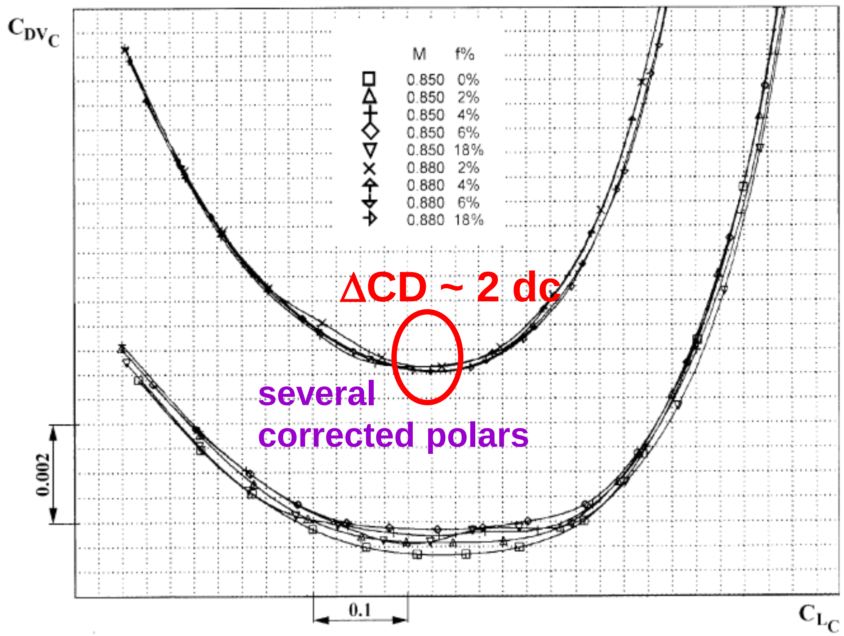
- High correction levels
  - Models for the effects
    - Empirical
    - Simplified CFD
  - Residual discrepancies

Free flow **Confined flow**



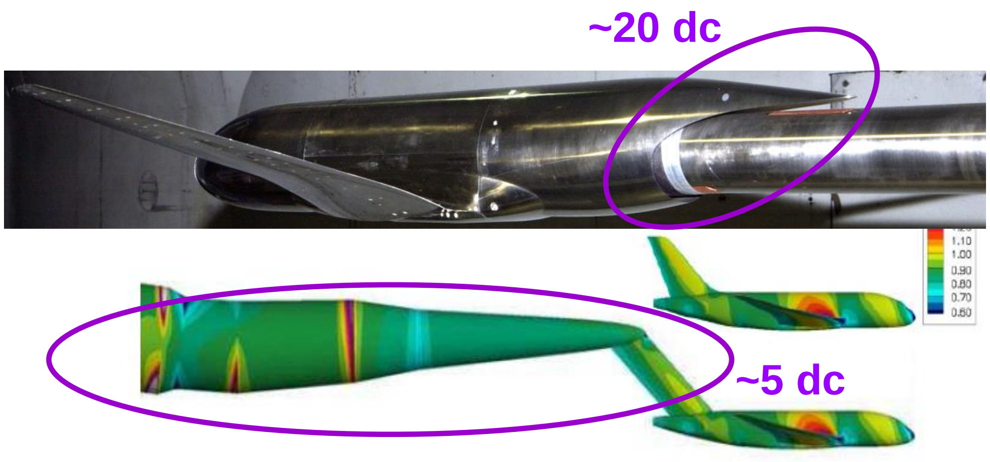
Glazkov et al
Recent experience in improving the accuracy of wall interference corrections in TsAGI T-128 wind tunnel
Progress in Aerospace, vol. 37, pp 263-298, 2001





CFD for EFD wall & mounting interference

- RANS CFD for EFD
  - Mounting effects
    - All stings are intrusive
    - Expensive correction through twin sting tests



Sylvain Mouton
Numerical Investigations of Model Support Interference in a Transonic Wind Tunnel
Colloque Aérodynamique Appliquée AAAF, 2009

  - Wall effects
    - Complete model of the wind tunnel
    - CFD captures the non linear corrections

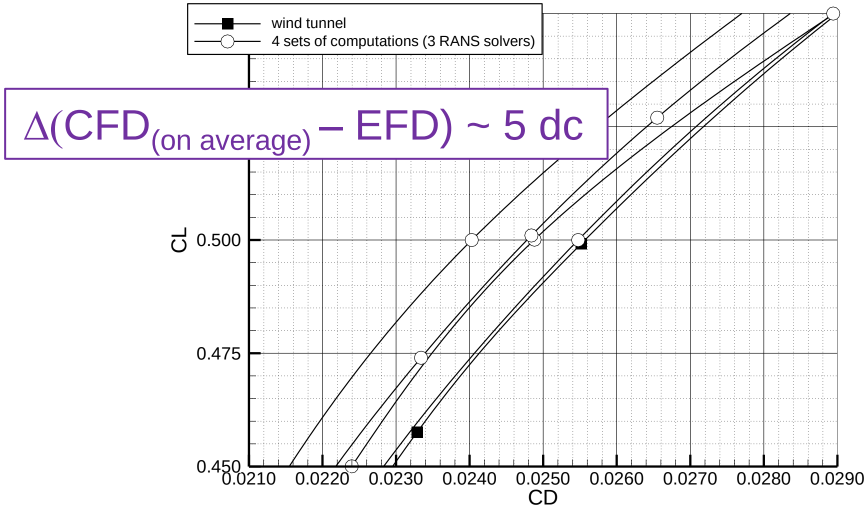
Validation of numerical simulations

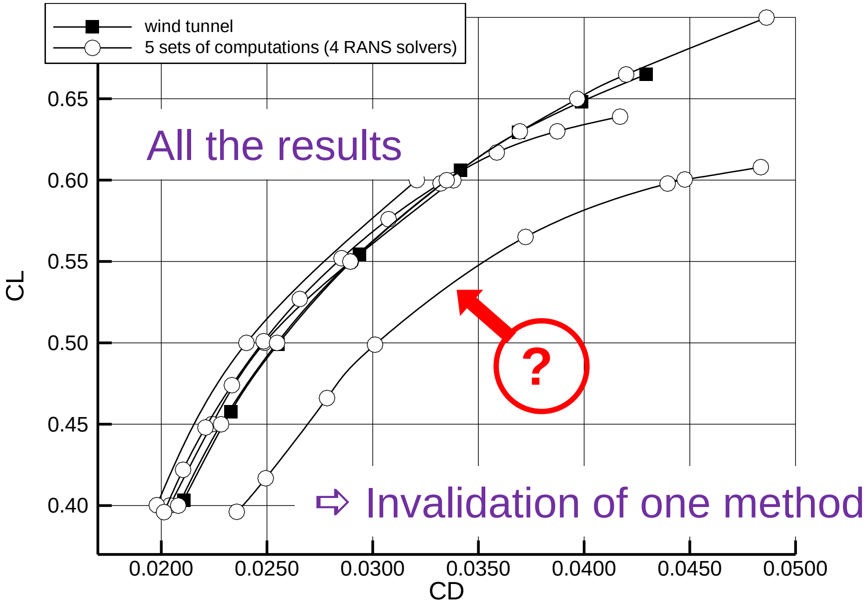
The validation paradigm

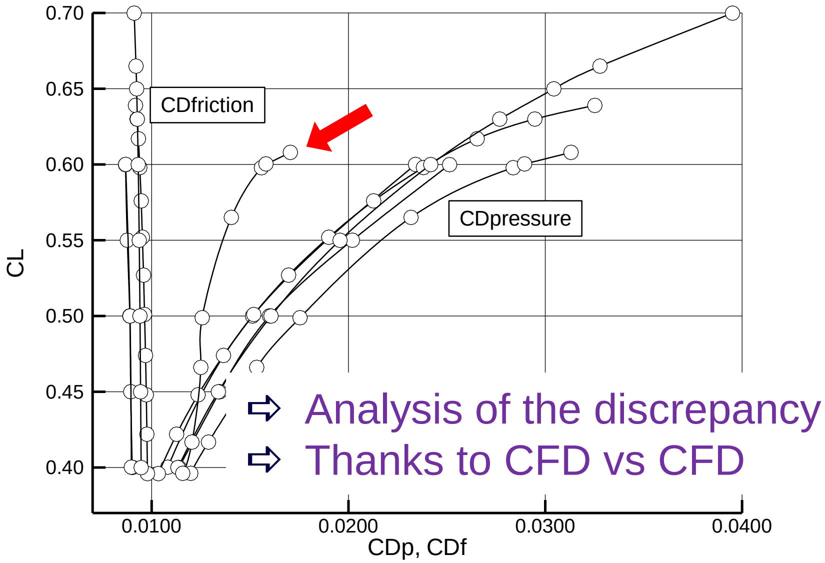
- Objective
  - CFD accuracy = EFD accuracy
- Conventional validation paradigm
  - Wind tunnel test is the reference
  - CFD codes are validated against EFD
  - International comparison exercises showing CFD progress… at cruise
- With the increasing use of CFD
  - CFD to prepare EFD
  - Wind test in depth analysis (bias, uncertainty…)
  - ⇨ What validates what?
- CFD / EFD validation
- CFD / CFD validation
- EFD / EFD validation
- (in)Validation examples

ONERA

Improvement in the RANS CFD method for cruise performance prediction







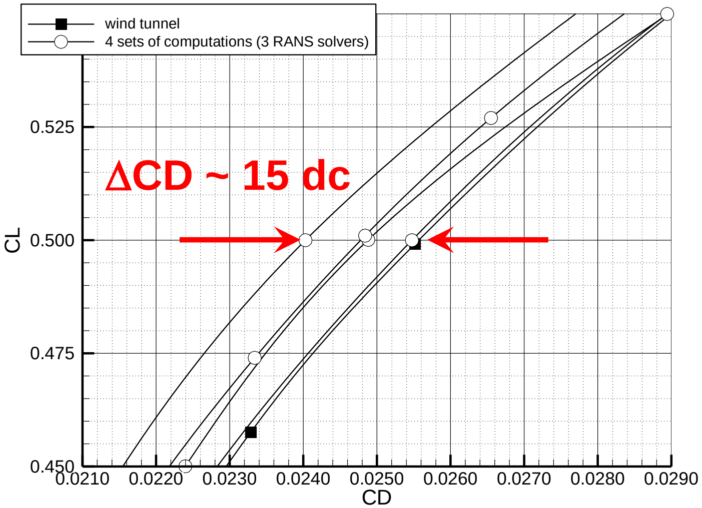
ONERA

Improvement in the RANS CFD method for cruise performance prediction

- CFD gets closer to… CFD
  - Significant decrease of the dispersion of many CFD predictions
  - Maturity in the CFD prediction of cruise performance

	standard deviation (σ)	
	DPW-1 computations (2001)	DPW-3 computations (2006)
CD	$21.\,10^{-4}$	$7.\,10^{-4}$

	standard deviation (σ)	
	GARTEUR AG05 (1988)	GARTEUR AG39 (2007)
CD	$10.\,10^{-4}$	$5.\,10^{-4}$

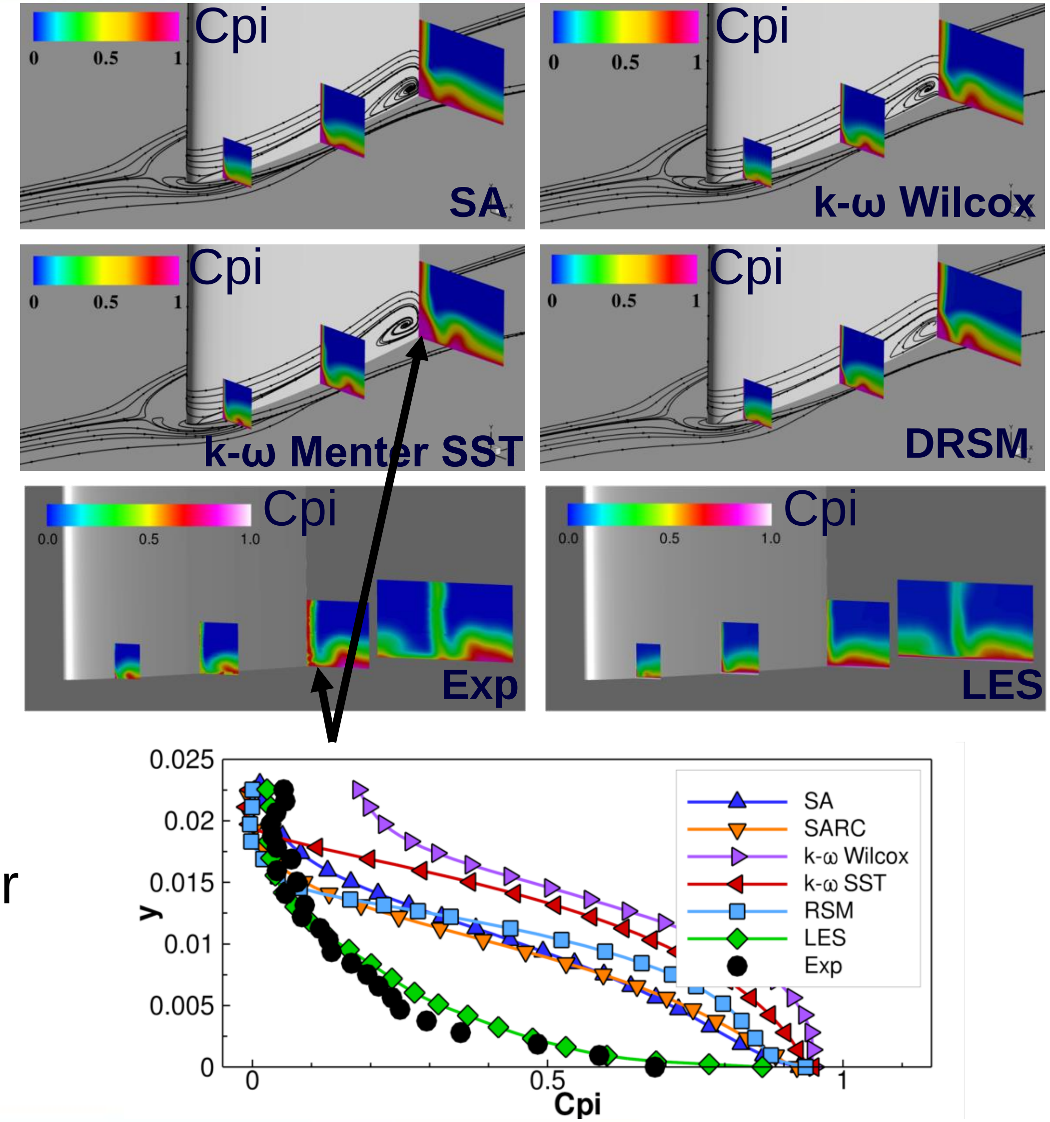


ONERA

CFD → EFD → CFD → EFD

Gand
Dynamique des écoulements de jonction en régime turbulent
PhD, Université Pierre et Marie Curie, 2011

- Corner flow study
  - Preparation of a reference test on corner flow separation
  - Rigorous RANS CFD analysis
    - Mesh convergence study
    - Several turbulence models
- Wind tunnel tests
  - No separation!
  - Further CFD analysis with LES
    - No separation in agreement with the tests
  - RANS invalidated
- New reference tests on corner separation
  - Available on the ONERA www



ONERA

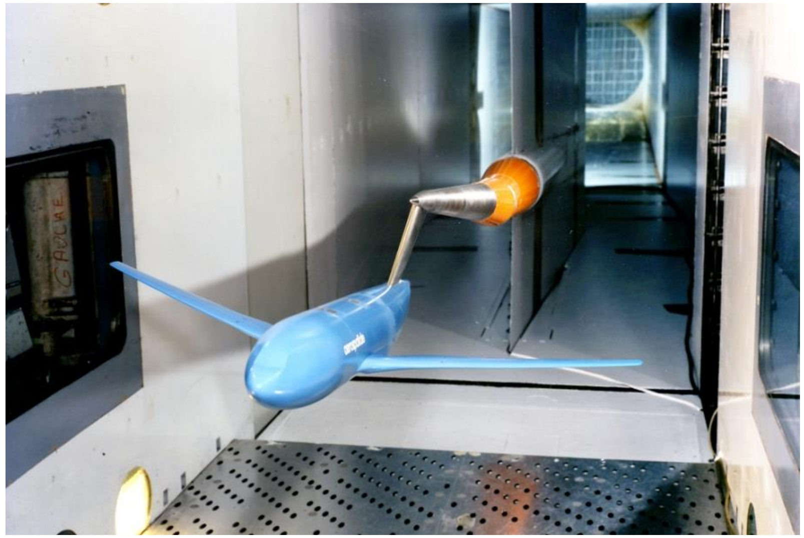
Conclusions

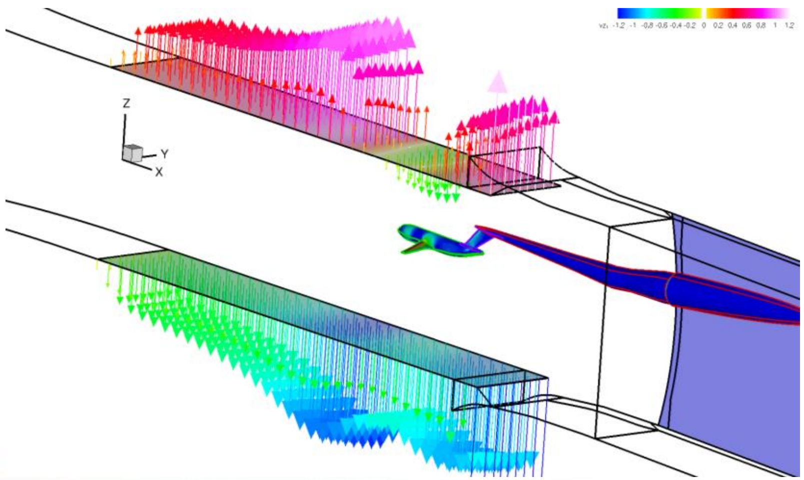
ONERA
THE FRENCH AEROSPACE LAB

Statements about validation

Hantrais-Gervois & Piat
A Methodology to Derive Wind Tunnel Wall Corrections from RANS Simulations
5th Symposium on Integrating CFD and Experiments in Aerodynamics 2012

- Objective
  - CFD accuracy = EFD accuracy
- CFD has made spectacular progress for cruise…
  - Major importance of the international comparison exercises
- … but it is not enough
  - Multi-purpose software may not yet reach these requirements
  - CFD is still a matter of dedicated codes
- EFD as a reference needs more and more solid ground
  - More and more in depth analysis of tests dedicated to validation
  - Trend to include the wind tunnel in CFD!





Statements about validation

It is not just the code that must be validated for its intended purpose, but also the entire process of geometry, grid generation, solver, post-processing of results, **and even the user** *that must be validated.* [1].

[1] TINOCO, E.N., *CFD Uncertainty and Validation for Commercial Aircraft Applications*, NATO Symposium AVT 147, Athens, Greece, December 3-6, 2007.

Statements about validation

If your computation predicts drag with an error of 2 to 5 drag counts, it is a good computation; if the prediction is perfect, something must be wrong with the computation; if the error is of 20 drag counts, something may be wrong with the experiment [1]. **Or we did not model the same thing!**

It is difficult, if not impossible, to put a precise numerical definition on what is CFD validation and when CFD is "good enough" ; but I know it when I see it [2].

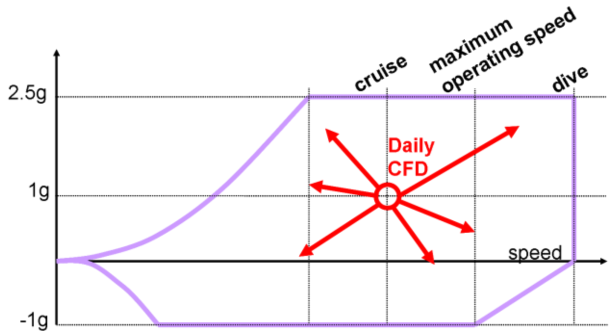
[1] DESTARAC, D., *Far-Field / Near-Field Drag Balance and Applications of Drag Extraction in CFD,* VKI Lecture Series 2003, CFD-based Aircraft Drag Prediction and Reduction, Rhode Saint Genèse (Belgium), February 3-7, 2003, National Institute of Aerospace, Hampton (VA), November 3-7, 2003.

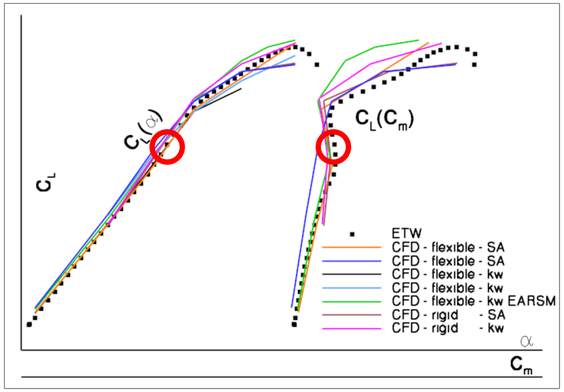
[2] TINOCO, E.N., *CFD Uncertainty and Validation for Commercial Aircraft Applications,* NATO Symposium AVT 147, Athens, Greece, December 3-6, 2007.

What about certification?

Hantrais-Gervois et al,
AG45 - application of CFD to predict high g loads
47th Int. Symposium of Applied Aerodynamics, 2012

- Presentation about cruise!
  - Convergence of international CFD
  - No major aerodynamic phenomenon
- Certification (flight part) is about off-design points
  - Brutal change in aerodynamics behaviour
    - Buffet
    - High lift stall
    - Research topics
  - Difficult with EFD to transpose to flight
    - High lift geometry and fixing structural parts
    - Highly sensitive phenomenon
  - Large scatter in the RANS CFD predictions
    - Not necessarily "conservative"
    - Expensive CFD to progress (ZDES / LES / DNS)
- Need for some inputs from industry





Thank you for your attention

Any question?

ONERA

THE FRENCH AEROSPACE LAB

return on innovation