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
• 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
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

\[
\text{range} \propto \frac{1}{\text{consumption}} \frac{MC_L}{CD} \log\left(\frac{\text{weight}_{\text{departure}}}{\text{weight}_{\text{arrival}}}\right)
\]

**Direct Operating Costs**
- Dollars/Nm/passenger

- **A380**: \( C_D + 1\% \Rightarrow \) cost 1-2 t more fuel
Civil aircraft certification topic

• 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)

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

Brunet

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
  - $M \times C_{L}/C_{D}$ or usually $C_{D}$
  - Clean wing
- Short range: climb and descent are more important than cruise
  - Optimise climb $C_{L_{\text{max}}}$ and $C_{L}/C_{D}$
  - High lift wing

\[C_{L} \approx 2.0\]
\[C_{D} \approx 0.20\]
\[C_{L}/C_{D} \approx 10\]

\[C_{L} \approx 0.5\]
\[C_{D} \approx 0.0250\]
\[C_{L}/C_{D} \approx 20\]

*From Gallard, PhD thesis 2014*

*Figure 1.1: Typical civil transport aircraft mission profile.*
Cruise drag

- 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

- Direct access to any physical quantity
- Repeatable
- Non intrusive
- RANS equations
- Perfect fluid
- Turbulence model
- Transition model
- Boundary conditions
- Time convergence
- Mesh convergence
- Rigid or aeroelastic CFD
- Ideal simplified CAD
- No roughness

Features

Models

Geometry

Process
EFD features

- repeatability checks...
- local intrusive indirect measure

models
- real fluid
- high turbulence level
- transition tripping
- mounting effects
- low Reynolds number
- continuous traverse

process

geometry
- too rigid model
- ideal simplified CAD
- polishing
- paint for measure
- milling tolerance
flight tests features

- hardly repeatable weather, pilot, loading
- local intrusive indirect measure
- deform. with fuel loading
- real with bolts & joins
- real fluid
- models
- geometry
- process
- measure on 30s level ground
CFD mesh convergence

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

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

Vassberg & Jameson

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

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

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

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

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

~20 dc
~5 dc
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**
Improvement in the RANS CFD method for cruise performance prediction

\[ \Delta(CFD_{\text{on average}} - EFD) \approx 5 \text{ dc} \]

All the results

\[ \Rightarrow \text{Invalidation of one method} \]

\[ \Rightarrow \text{Analysis of the discrepancy} \]

\[ \Rightarrow \text{Thanks to CFD vs CFD} \]
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

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<td>DPW-1 computations</td>
<td>DPW-3 computations</td>
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<tr>
<td>$CD$</td>
<td>$21 \times 10^{-4}$</td>
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<tr>
<td>GARTEUR AG05</td>
<td>GARTEUR AG39</td>
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<tr>
<td>$CD$</td>
<td>$10 \times 10^{-4}$</td>
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$\Delta CD \sim 15 dc$
• 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
Conclusions
Statements about validation

- **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!
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].

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].


What about certification?

- 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?