Part 3.

Brief introduction to CFD

How to compute/estimate the aerodynamic charateristics of bodies/wings?

How to compute/estimate the aerodynamic charateristics of bodies/wings?

- So far, we have studied the LLT, VLM and 3D panel methods.
- CFD (**C**omputational **F**luid **D**ynamics), is the next method in our classification.
- CFD is much more accurate than all the previous methods explored (potential methods).
- It is also much more expensive.
- And it requires a lot of user experience.
- A lot of the sources of uncertainty are involved when conducting CFD studies:
    - Models (turbulence, acoustics, mass transfer, radiation, etc.)
    - Element type and mesh quality.
    - Numerical method and discretization schemes.
    - Boundary conditions and initial conditions.
    - Convergence criterion.
    - Machine precision.
    - Parallelization
    - Hardware architecture.
    - and so on.

How to compute/estimate the aerodynamic charateristics of bodies/wings?

- When doing the initial design, you will be tempted to use CFD.
- However, <u>CFD is too expensive to be used during the preliminary design phase</u>.
    - CFD can be used to fine tune your design at a later stage.
- But if there is no other choice, or if you have enough time and resources, feel free to use CFD.

- Semi-empirical methods.
- Prandtl lifting-line theory (LLT).
- Vortex lattice methods (VLM).
- 3D panel methods.
- Computational fluid dynamics.

Less

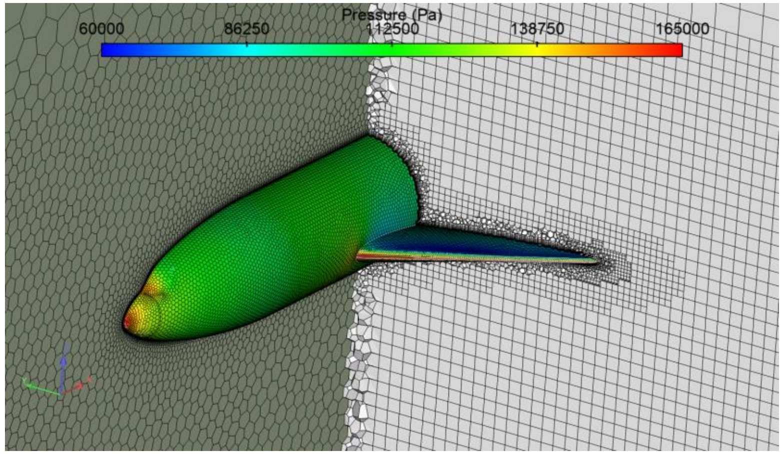
↓

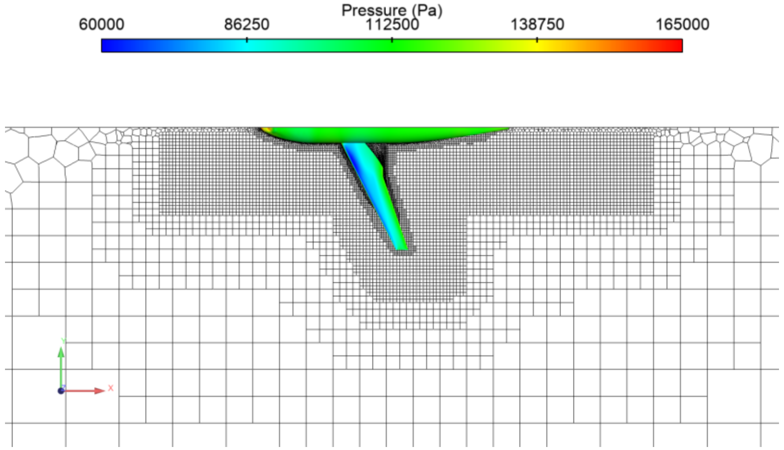
More

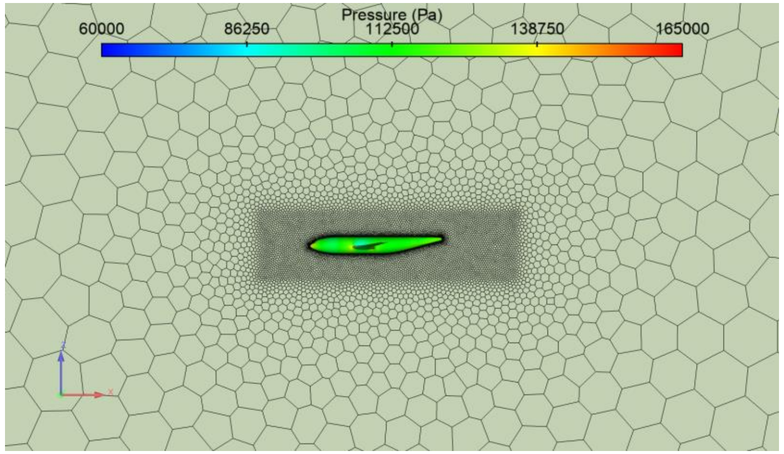
- Mathematical and computational complexity.
- Physics involved.
- Computational resources.
- Simulation time.
- User experience.
- Accuracy.

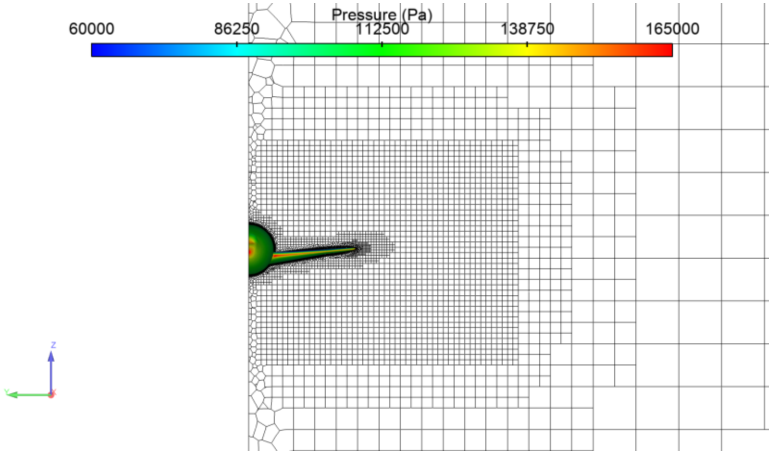
How to compute/estimate the aerodynamic charateristics of bodies/wings?

- Let us move from sources, doublets, vortex filaments, horseshoe vortices, panels, and so on, to the most accurate method to predict the aerodynamic performance of bodies, namely, CFD.
- In CFD, we numerically approximate the governing equations in a discrete domain (computational mesh).
- The solution is sought in every single cell of the computational mesh.









How to compute/estimate the aerodynamic charateristics of bodies/wings?

- As we are dealing with fluid dynamics (aero/hydro dynamics), the governing equations of the physics involved are the Navier-Stokes equations,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$
$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot \tau,$$
$$\frac{\partial (\rho e_t)}{\partial t} + \nabla \cdot (\rho e_t \mathbf{u}) = \nabla \cdot q - \nabla \cdot (p \mathbf{u}) + \tau \mathbf{:} \nabla \mathbf{u},$$

$$+$$

Additional equations derived from models, such as, turbulence modeling, chemical reactions, combustion, acoustics, multi-species, particle interaction, mass transfer, dispersed phases, separated flows, thermodynamical models, and so on.

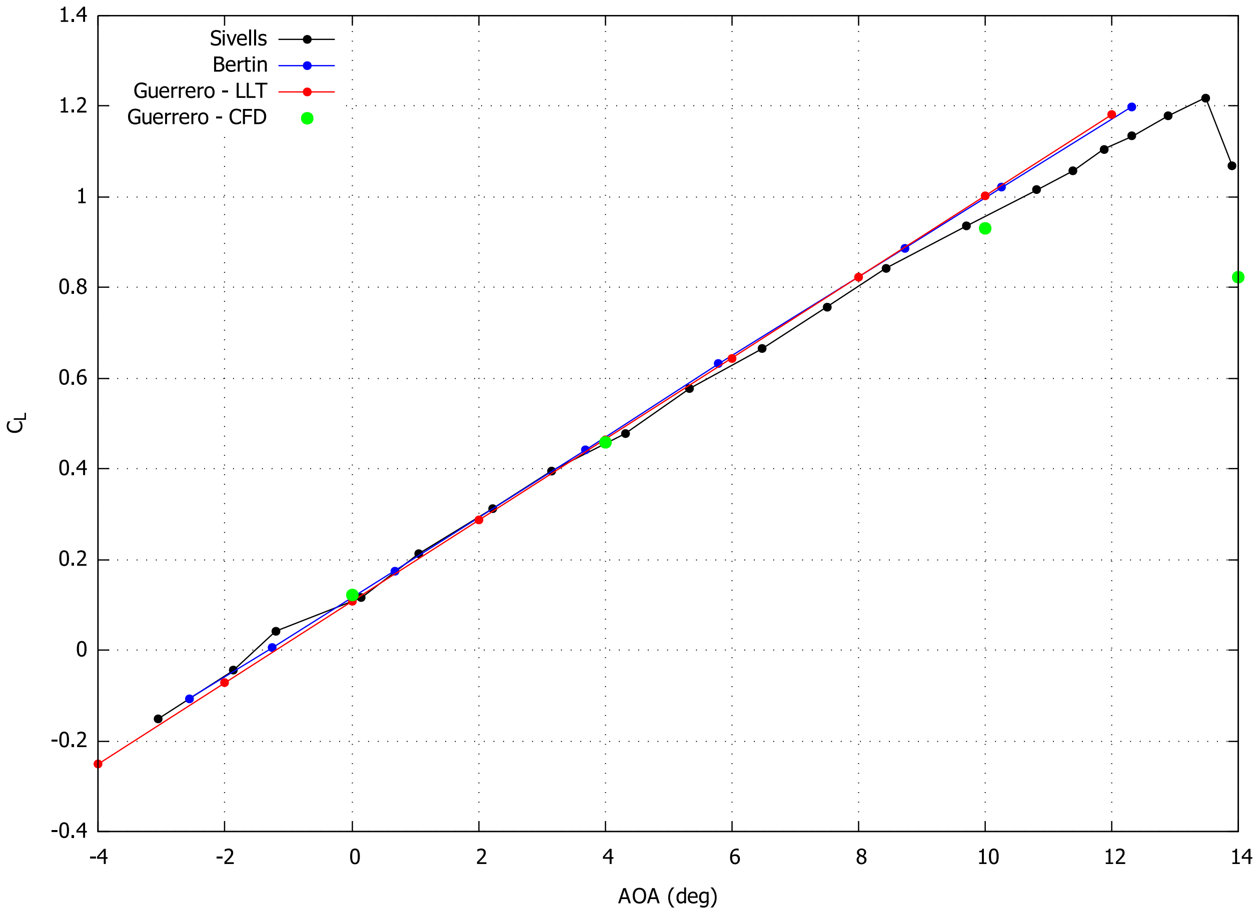
$$+$$

Boundary conditions and initial conditions.

Comparison of different methods

Comparison of different methods

- Comparison of different methods.

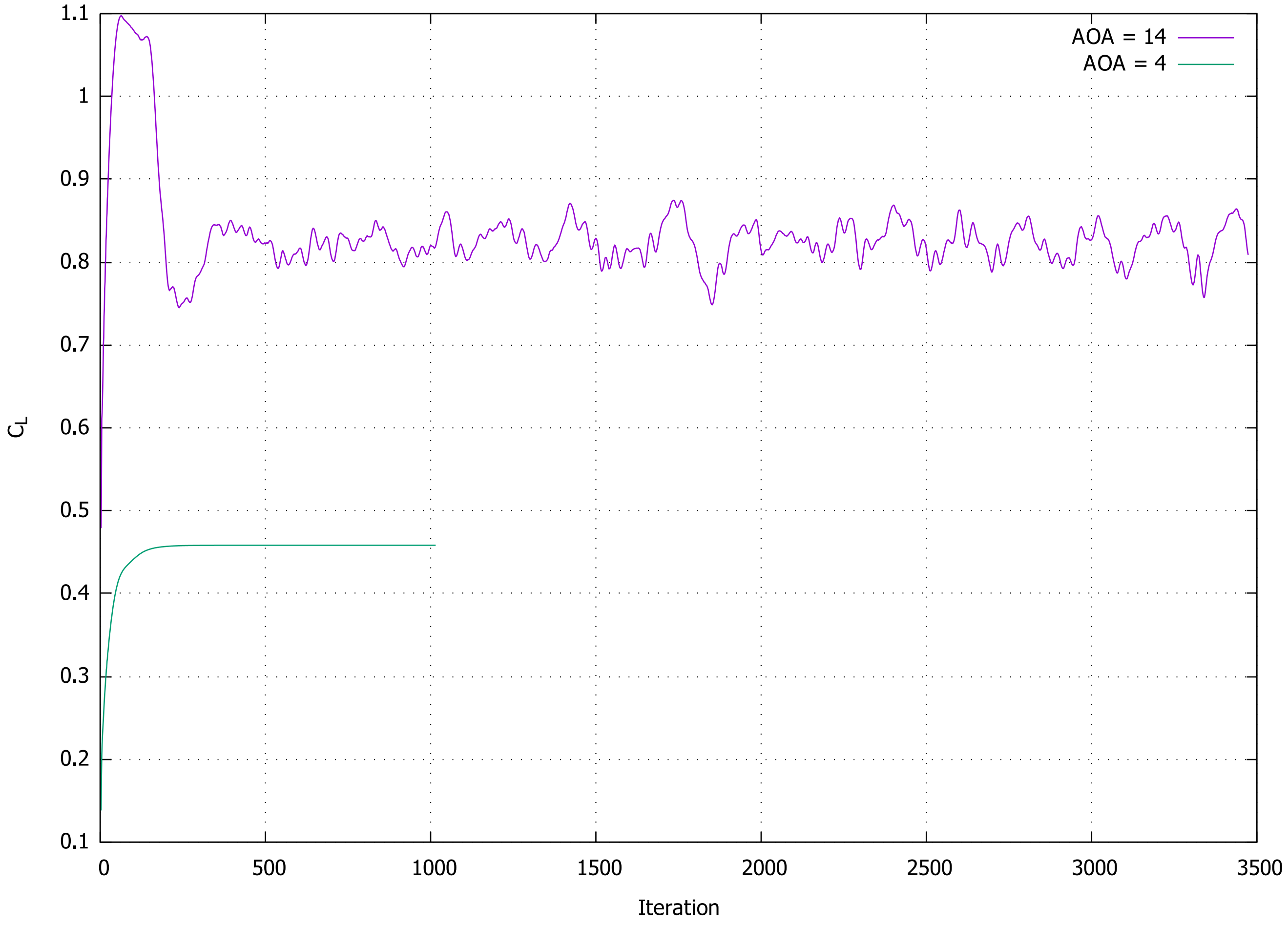


- Each CFD simulation took approximately 20 minutes in a rather coarse mesh.
- Each simulation generated a large amount of data.
- The meshing time is about 2 minutes for every different configuration.
- The initial geometry generation took about 1 hour.
- If everything is properly parametrize, geometry and meshing time is no more than 3 minutes.
- The postprocessing time depends on what we are interested in.
- These estimates are for a experienced user.

- Data source:
  - J. Sivells. Experimental and calculated characteristics of three wings of NACA 64-210 and 65-210 airfoil sections with and without washout. NACA Report 1422, 1947.
  - Aerodynamics for Engineers (6th Edition). J. Bertin, R. Cummings. Pearson, 2013.

Comparison of different methods

- Comparison of the outcome at two different AOA.



- At AOA 4° the flow shows a steady and non-oscillatory behavior.
- That is, after 500 iterations the solution does not change.
- Instead, at AOA equal to 14° the flow is highly unsteady (or oscillatory), the solution change from iteration to iteration.
- Assessing convergence with highly unsteady flows is tricky.
- It requires to run the simulations for long times in order to get an average solution.

So, what can CFD do that the other methods cannot?

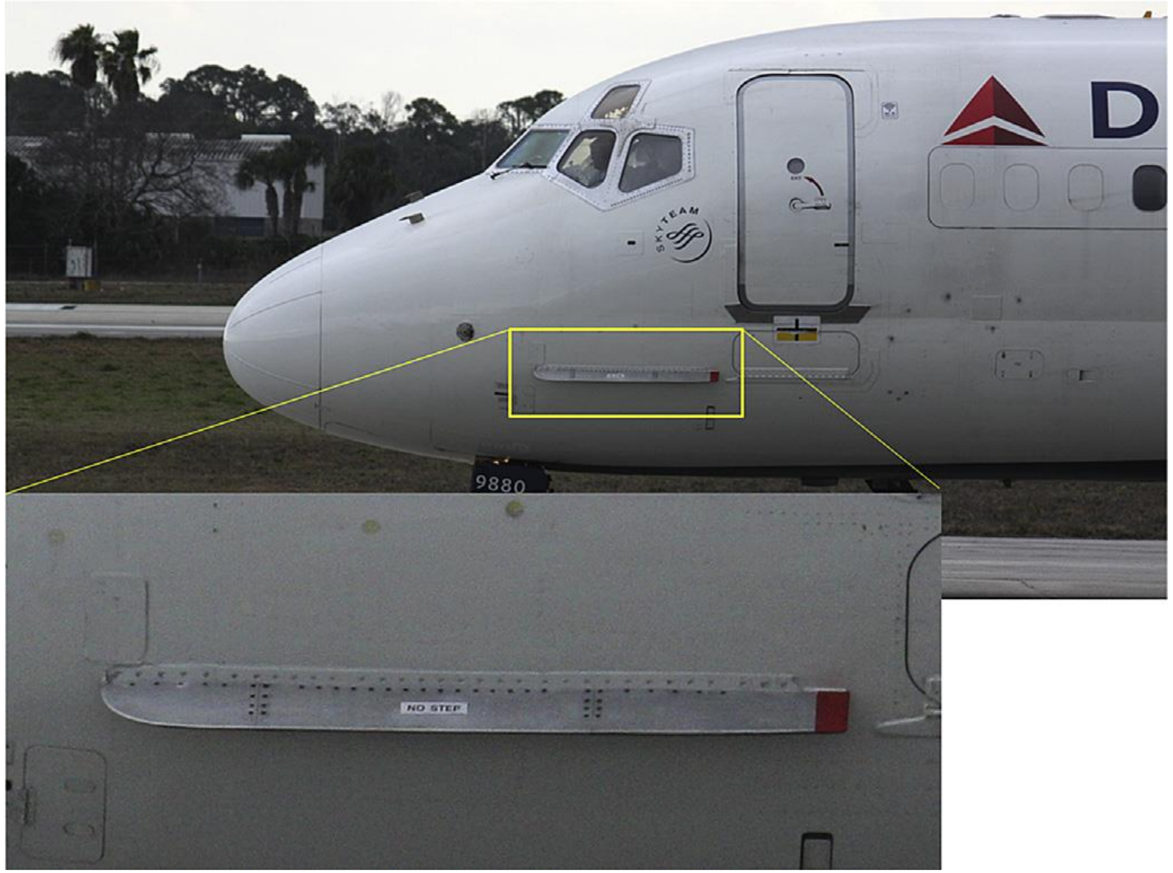
So, what can CFD do that the other methods cannot?

- In few lines, CFD can capture the physics related to:
  - Three-dimensional effects.
  - Highly unsteady dynamics.
  - Interaction between components.
  - Complex physical modeling, such as,
    - Turbulence, heat transfer, radiation, aero-acoustics, phase change, free surfaces, chemical reactions, combustion, fire dynamics, particle dynamics, pharmacokinetics, moving bodies, supersonic flows, fluid-structured interaction, and so on.

- In addition, CFD results give more information at post-processing time.

So, what can CFD do that the other methods cannot?

- In few words, three-dimensional effects, interaction between components, and complex physical modeling (turbulence, heat transfer, radiation, aero-acoustics, phase change, free surfaces, chemical reactions, combustion, fire dynamics, particle dynamics, pharmacokinetics, moving bodies, and so on).



Ventral fins, fuselage strakes, stabilons and taillet

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Stall strip and wing fences

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Vortex generators and vortilons

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Winglets and wingtip devices

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Nacelle strakes

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Stall patterns

So, what can CFD do that the other methods cannot?

- In few words, three-dimensional effects, interaction between components, and complex physical modeling (turbulence, heat transfer, radiation, aero-acoustics, phase change, free surfaces, chemical reactions, combustion, fire dynamics, particle dynamics, pharmacokinetics, moving bodies, and so on).

High lift devices (flaps and slats) and saw-teeth (chevrons) on engine nozzle

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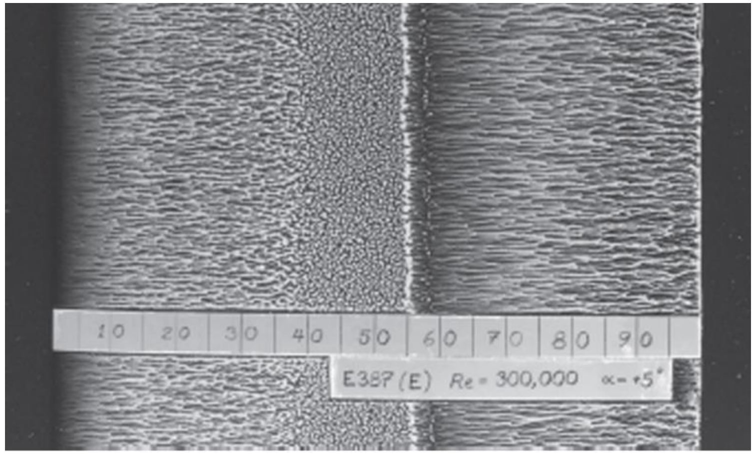
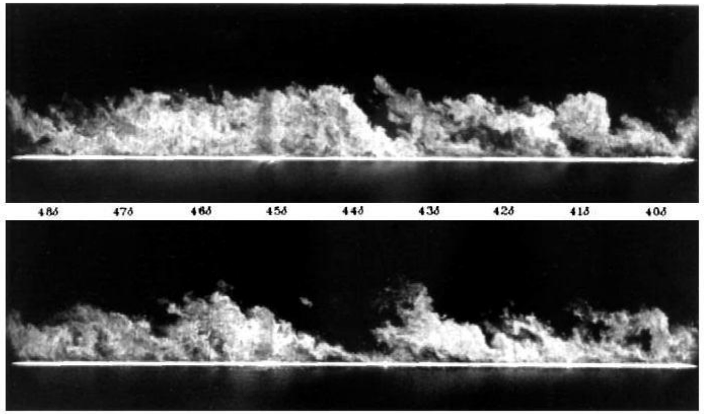
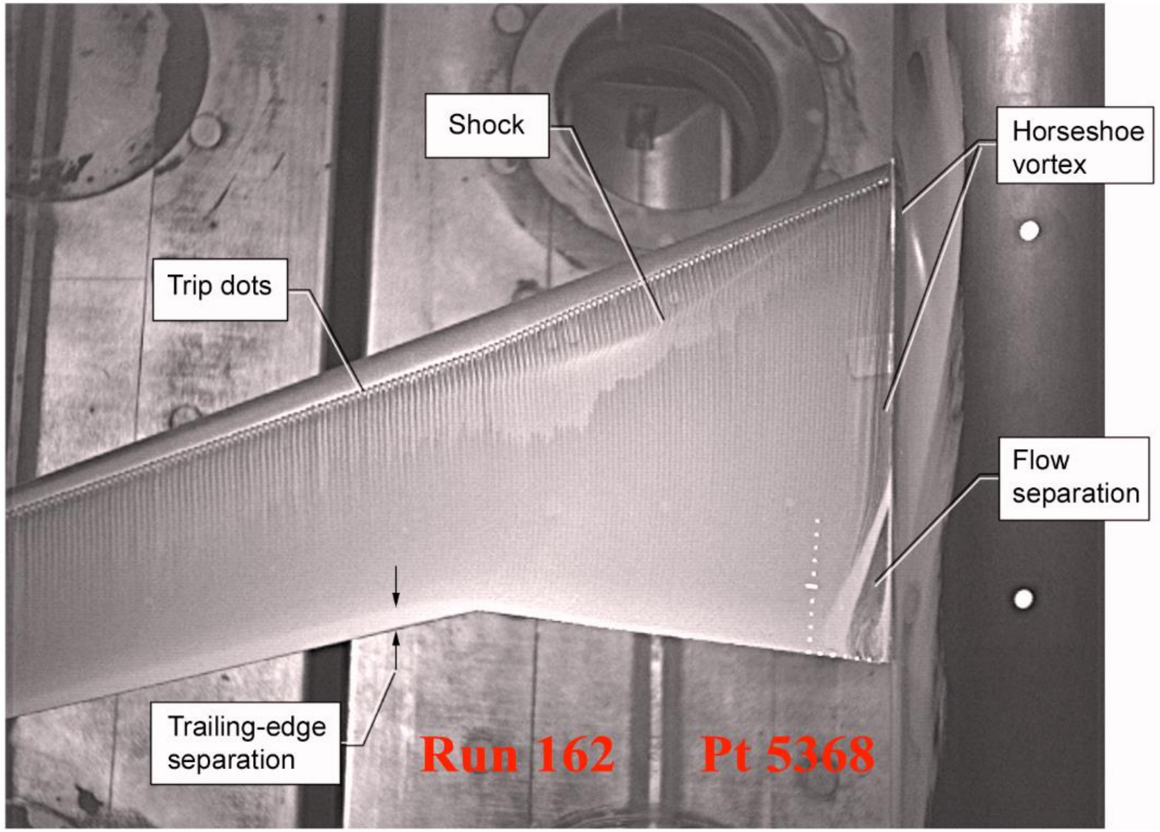






Quantitative and qualitative characterization of boundary layers, laminar separation bubbles, and wing-fuselage separation (separation of bubble or SOB)

So, what can CFD do that the other methods cannot?

- In few words, three-dimensional effects, interaction between components, and complex physical modeling (turbulence, heat transfer, radiation, aero-acoustics, phase change, free surfaces, chemical reactions, combustion, fire dynamics, particle dynamics, pharmacokinetics, moving bodies, and so on).

Ice formation and accretion

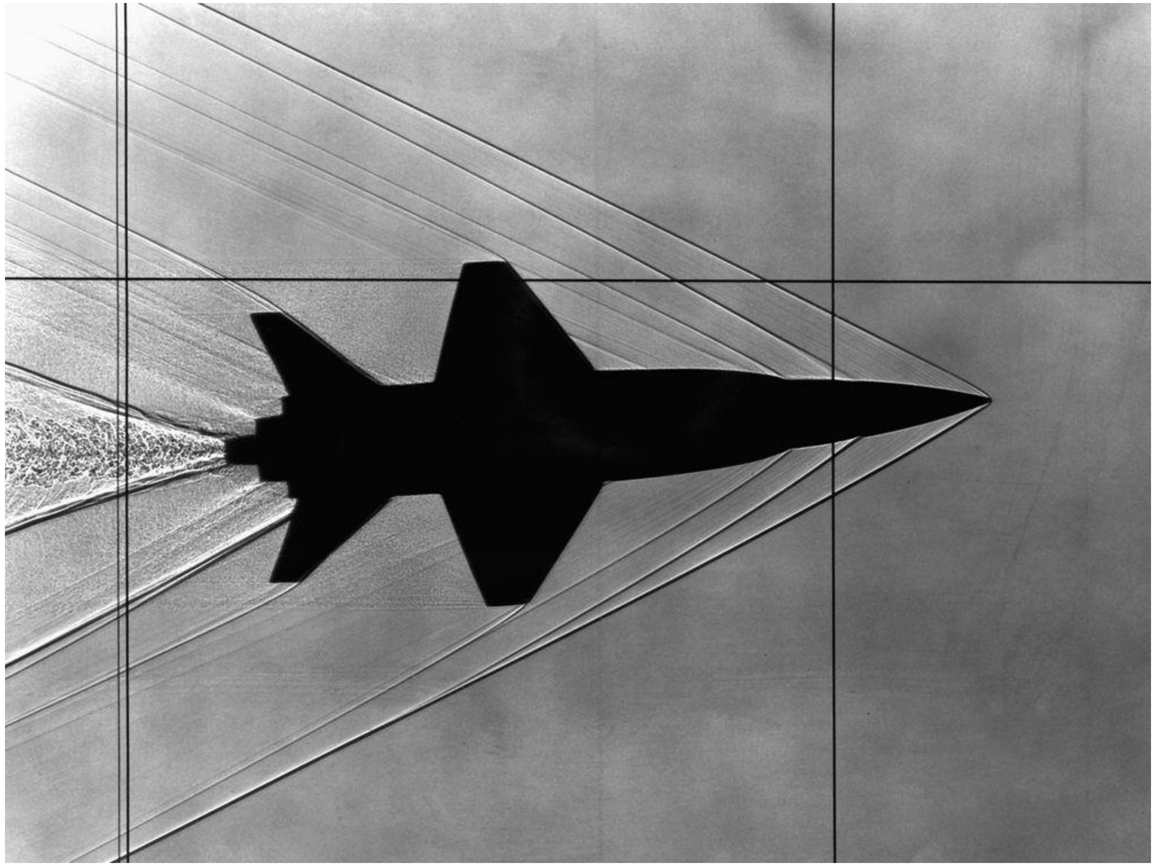
So, what can CFD do that the other methods cannot?

- In few words, three-dimensional effects, interaction between components, and complex physical modeling (turbulence, heat transfer, radiation, aero-acoustics, phase change, free surfaces, chemical reactions, combustion, fire dynamics, particle dynamics, pharmacokinetics, moving bodies, and so on).

Engine inlets

So, what can CFD do that the other methods cannot?

- In few words, three-dimensional effects, interaction between components, and complex physical modeling (turbulence, heat transfer, radiation, aero-acoustics, phase change, free surfaces, chemical reactions, combustion, fire dynamics, particle dynamics, pharmacokinetics, moving bodies, and so on).



Shock waves and vapor cones

So, what can CFD do that the other methods cannot?

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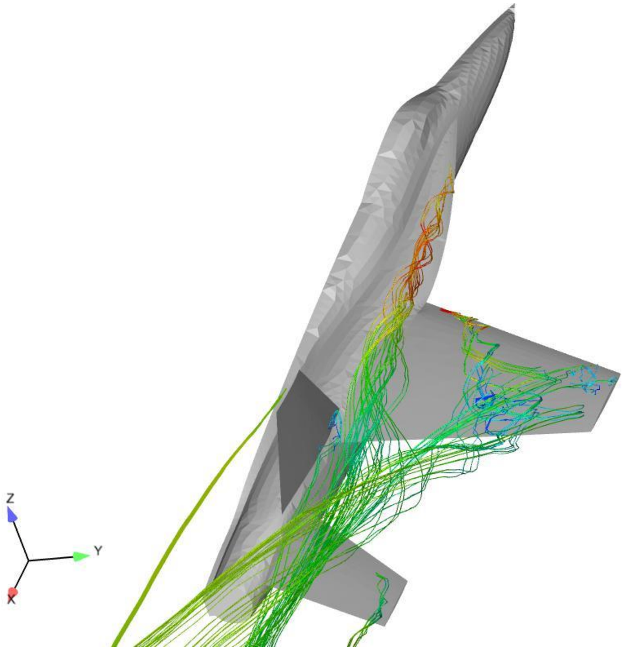

Leading edge extensions (LEX) vortices

CFD in industry

CFD in industry

- There is a clear trend in industry (not only aerospace industry), where CFD is seen as a tool to certify products by analysis and simulations.
    - This is known as certification by analysis or CbA.

- In general, industry is shifting towards fully utilizing Model Based Engineering to simulate products and their lifecycle.
    - This is known as Digital Twins.
    - Multi-physics simulations, reduce-order models, and the internet-of-things (IoT) are integral part of Digital Twins.

- In the aerospace industry, Computational Fluid Dynamics (CFD) is expected to play an increasingly significant role in achieving dramatic reductions in flight testing through CbA.

CFD in industry

- The following presentations worth reading (related to the aerospace industry):
  - Future directions in computational simulations to enable certification and qualification by analysis. R. Gregg and J. Slotnick – Boeing Commercial.
    - https://scientific-sims.com/cfdlab/WORKSHOP/assets/TALKS/gregg.talk.pdf
  - Future Directions of Computational Fluid Dynamics. F. D. Witherden and A. Jameson – Stanford University.
    - http://aero-comlab.stanford.edu/Papers/aiaa_cfd_future_2017.pdf
  - An industrial view on numerical simulation for aircraft aerodynamic design. A. Abbas-Bayoumi and K. Becker – Aerodynamic Strategies, Airbus.
    - https://link.springer.com/article/10.1186/2190-5983-1-10
  - CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences.
    - https://ntrs.nasa.gov/citations/20140003093
    - http://www.cfd2030.com/

CFD in industry

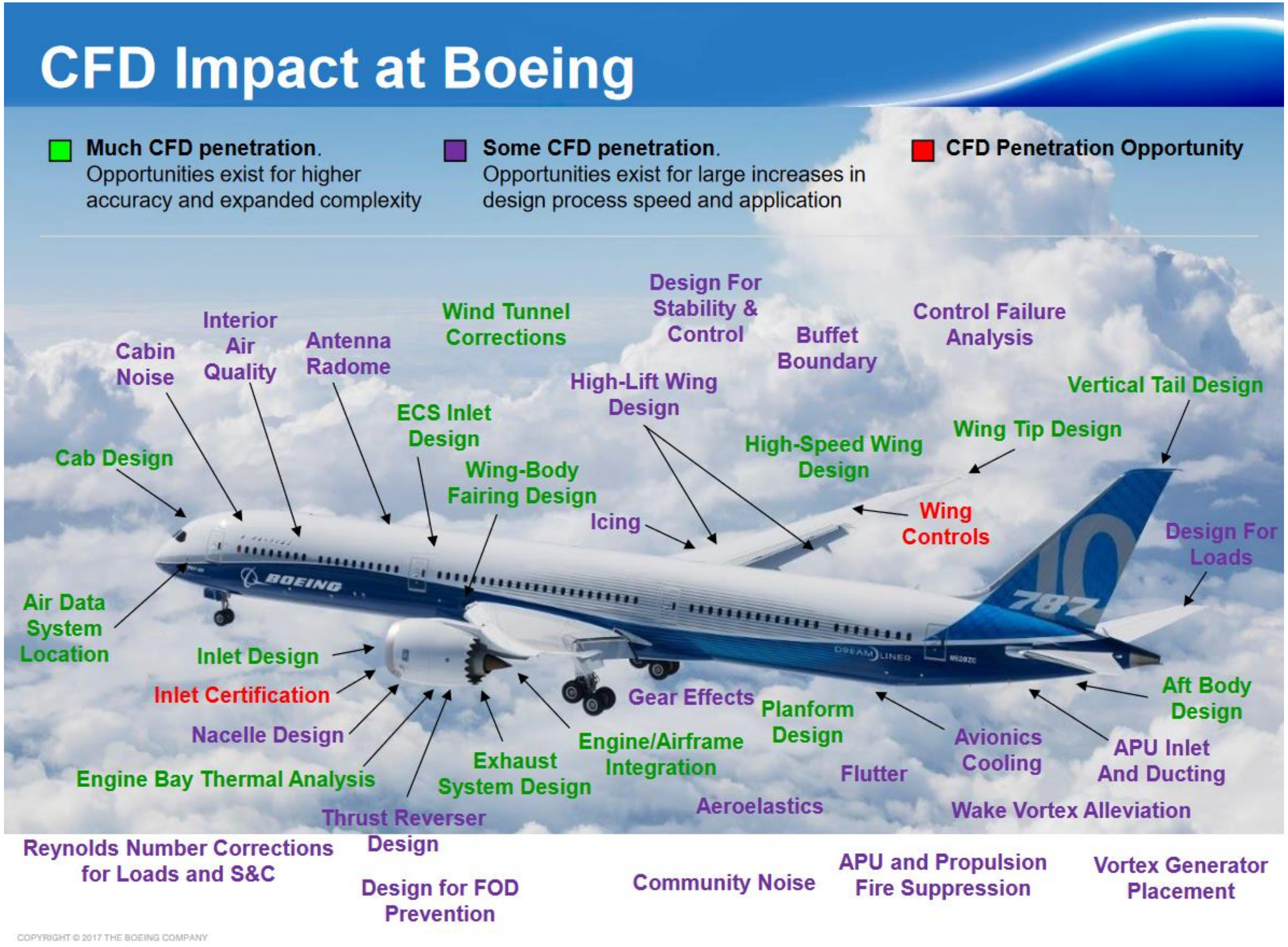

Photo credit: Future directions in computational simulations to enable certification and qualification by analysis. R. Gregg and J. Slotnick.

CFD in industry

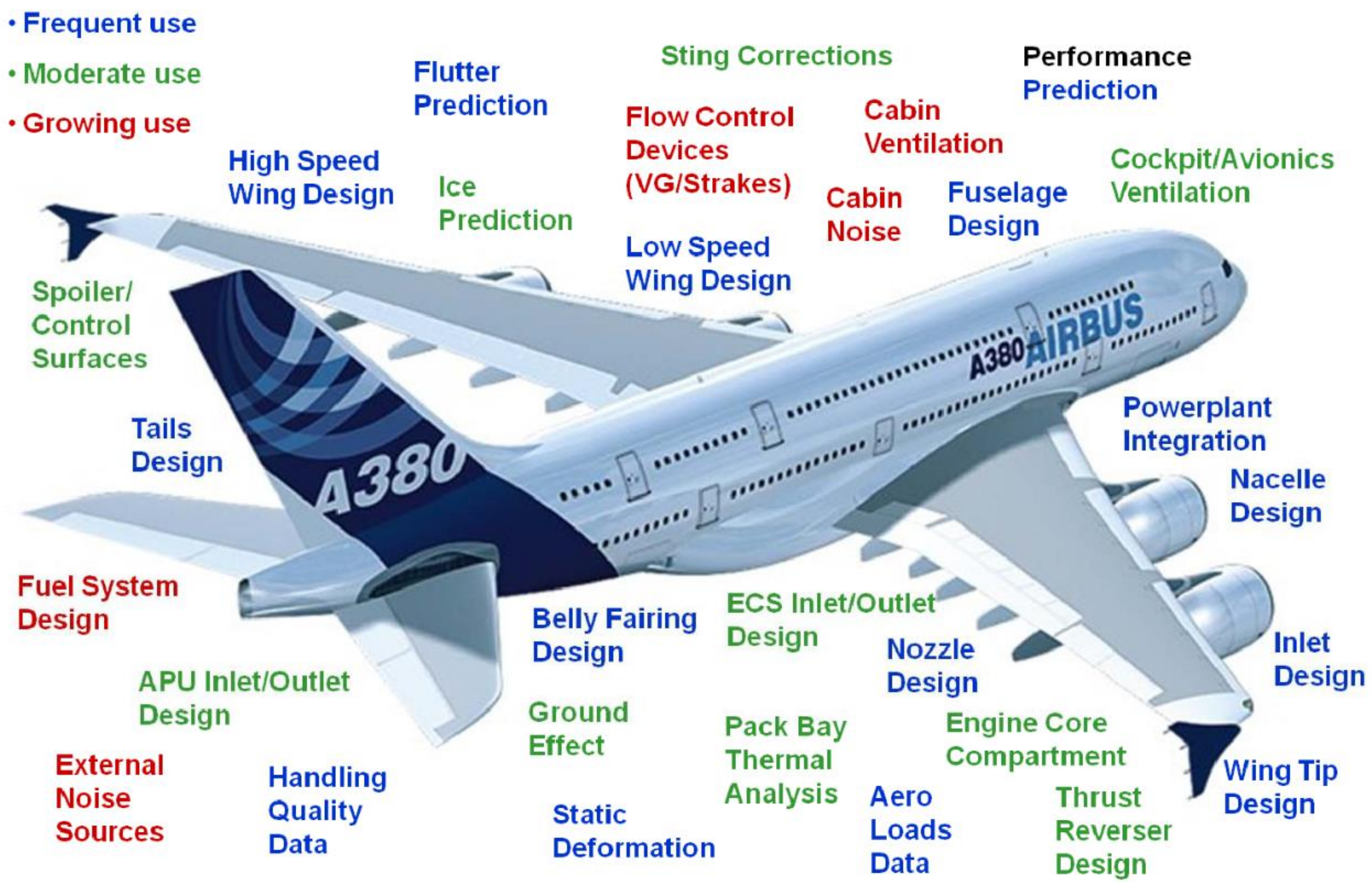

Photo credit: An industrial view on numerical simulation for aircraft aerodynamic design. A. Abbas-Bayoumi and K. Becker .

Physical experiments versus numerical simulations

Physical experiments versus numerical simulations

- Will CFD replace physical experiments?
    - In some situations, yes.
    - And in some other situations no, at least for the moment.
    - In general, CFD complements testing and experimentation.
        - As there are not many analytical solutions around, experiments are used to validate CFD simulations.
    - CFD can help to reduce the amount of experimentation and the overall cost of the physical experimentation.

Physical experiments versus numerical simulations

- Interesting references:
  - Symbiosis: Why CFD and wind tunnels need each other
    - https://aerospaceamerica.aiaa.org/features/symbiosis-why-cfd-and-wind-tunnels-need-each-other/
  - Why we’re not there yet on CFD
    - https://aerospaceamerica.aiaa.org/departments/why-were-not-there-yet-on-cfd/
  - New techniques and results enhance physical understanding
    - https://aerospaceamerica.aiaa.org/year-in-review/new-techniques-and-results-enhance-physical-understanding
  - Will CFD ever Replace Wind Tunnels for Building Wind Simulations?
    - https://global.ctbuh.org/resources/papers/download/4200-will-cfd-ever-replace-wind-tunnels-forbuilding-wind-simulations.pdf
  - On the role and challenges of CFD in the aerospace industry
    - https://www.cambridge.org/core/journals/aeronautical-journal/article/on-the-role-and-challenges-of-cfd-in-the-aerospace-industry/AB70FEF00301B20648F5B0627893B787
  - The CFD Vision 2030
    - https://www.cfd2030.com/index.html

Physical experiments versus numerical simulations

- The results of CFD simulations are never 100% reliable.
- Sources of error in CFD:
    - Round-off errors (computer precision).
    - Iteration errors.
    - Discretization errors.
    - Modeling errors.
    - User errors.
    - Programming errors.
- Also, experiments are never 100% reliable.
- So, you must be very critical when assessing the results.

Physical experiments versus numerical simulations

- Physical experiments versus numerical simulations – Comparison of different metrics.

Metric	Physical experiments	Numerical simulations
Cost	They can be very costly	Compared to physical experiments, they cost much less
Time to set a case	Short to long	Short to medium
Time to run	Short to long	Short to long
Scaling	Small to middle	Any scale
Information	Measured point and quantity. Intrusive	Everything, anywhere. Non-intrusive
Repeatable	Some. Limited by cost and time	Yes
Concurrency	Some. Limited by cost and time	Yes
Safety	They might be dangerous	Safe
Optimization	Yes, but high cost of the prototype	Yes
Uncertainty	Yes	Yes. Maybe higher than physical experiments

Physical experiments versus numerical simulations

- Comparison of CFD simulations and physical experiments costs.
- Rule of thumb for airplane design – Costs of numerical simulations, wind tunnel testing and flight test.

1 hour of CFD* - Approximately 1k $

1 hour of wing tunnel - Approximately 10k $

1 hour of flight test - Approximately 100k $

* Large simulations