# Towards leveraging high resolution simulations to investigate the operation of ~~multi-hole probes~~ devices for very precise measurements in challenging regimes

*AIAA Turbine Engine Testing Working Group MEETING 114*

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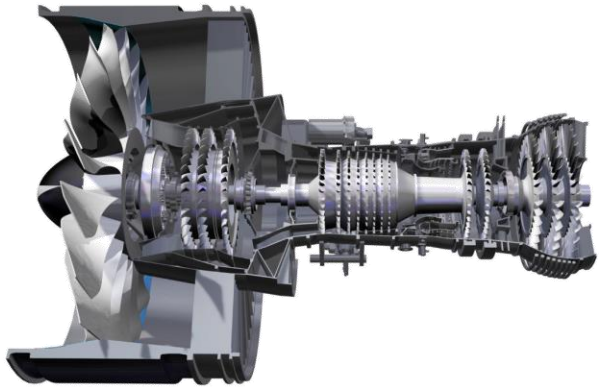
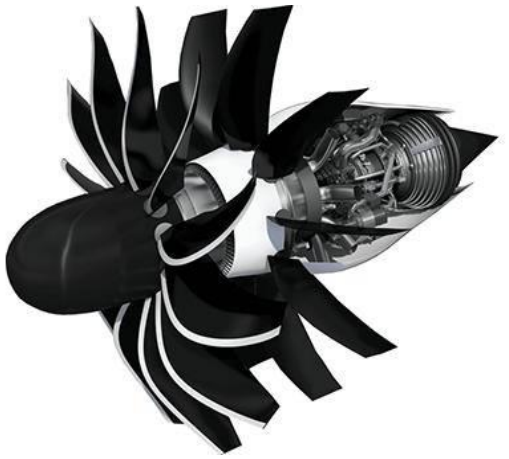
# Evolution towards high speed, low Re turbomachinery

## Future engines : geared low pressure spool

- Geared turbofan
- Unducted fan



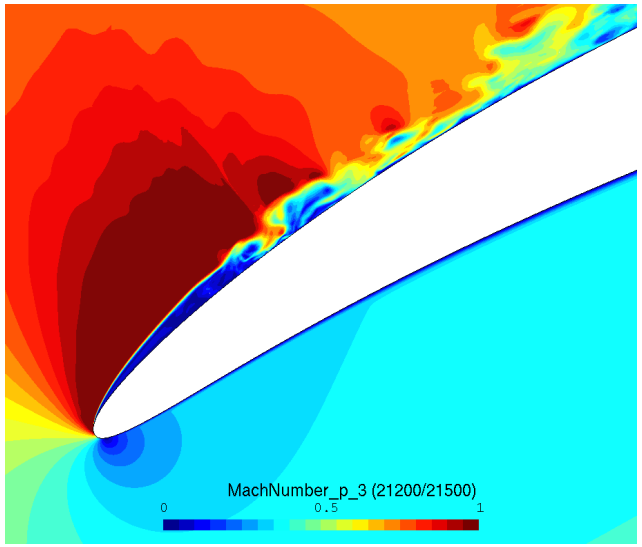


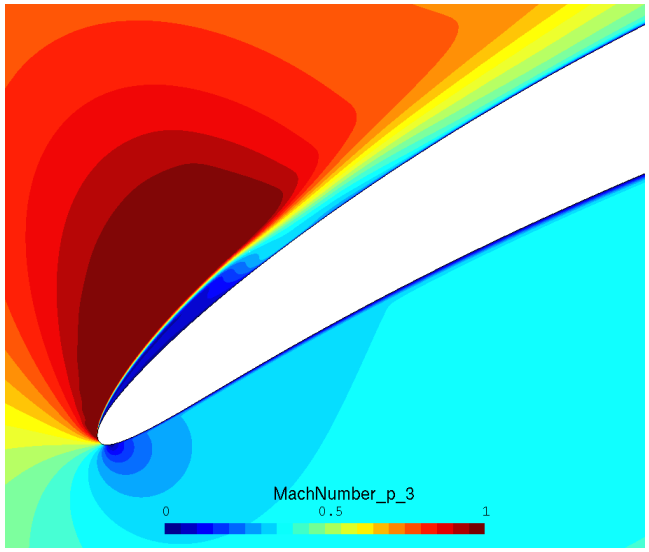
## Specific flow regimes on fast low-pressure spool

- Low Reynolds flow -> laminar separation, large scale turbulence
- High Mach number -> acoustic waves, shocks

## Challenges for simulation

- RANS and transition models inadequate (industrial standard)
- Scale resolving simulations required to understand flow and validate / improve engineering models (RANS, loss models, …)
- Virtual experiments needed for model independence




## Challenges for physical experiments

- Large turbulent flow structures with respect to probes
- Low-Reynolds effects on probe
- Compressible / acoustic / shock effect

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# Scale-resolving simulations

*Virtual experiments*

## Turbulence spectrum ~ E(k), k ~ 1/l

- Production range -> flow separations etc.
- Inertial range -> Taylor microscale – inviscid decomposition
- Dissipation range: Taylor -> Kolmogorov scale

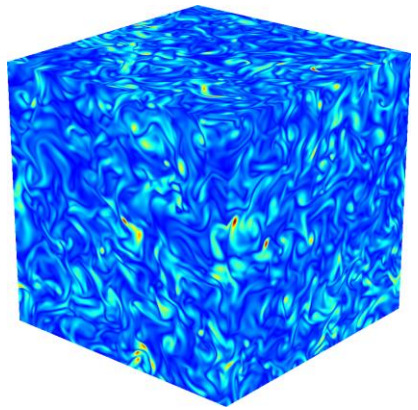
## Scale Resolving Simulations

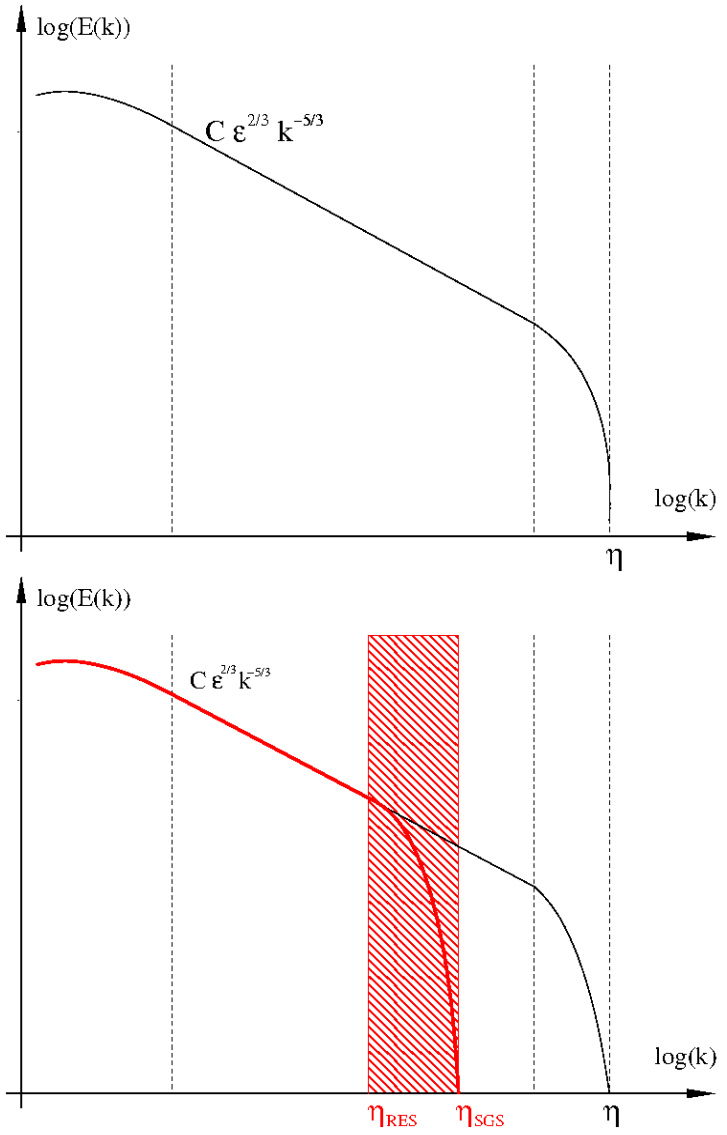
- Direct Numerical Simulation – no model
- Large Eddy Simulation – subgrid scale model + sacrificial range
- Wall modeled LES : model for boundary layers
  - Hybrid RANS-LES (DES)
  - Wall-shear stress modeled LES

## Challenges for virtual experiments

- High precision numerics required
- Long term integration (if statistics required)
- Shocks and acoustic effects
- Complex geometry

## Close Integration with physical experiments desired



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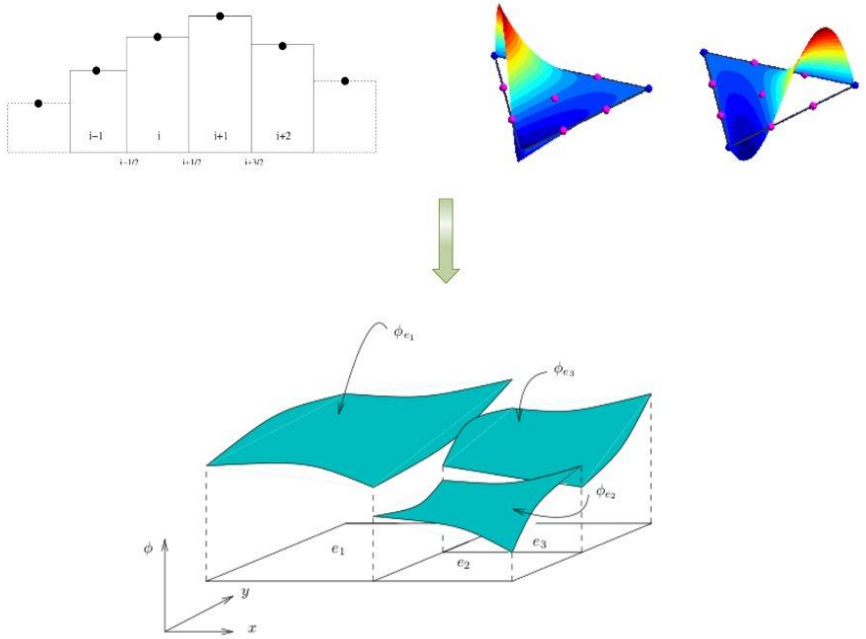
# Discontinuous Galerkin Method code ArgoDG (Cenaero)

*ArgoDG (Cenaero) -Enabling academic precision on industrial geometry*

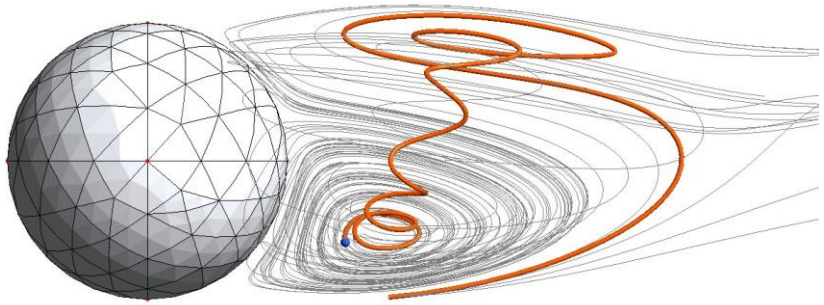
## Discontinuous Galerkin Method (DGM)

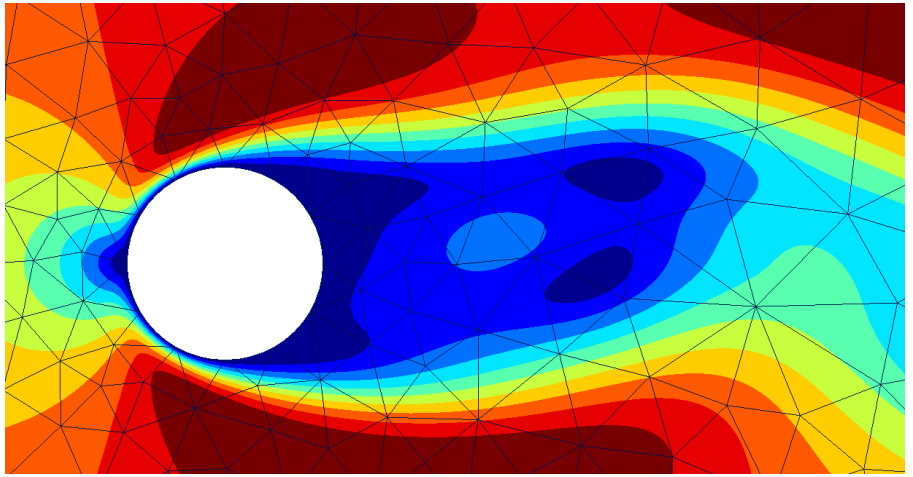
- Finite Element (FEM) inside the element
- Finite Volume (FVM) on element boundaries




## Advantages

- Stability of FVM for convective problems
- Geometrical precision of FEM
- Arbitrary order guaranteed on unstructured meshes
- hp-adaptivity
- Low degree of freedom count for given accuracy
- Computational compacity -> efficiency, parallel performance on large scale computational infrastructure





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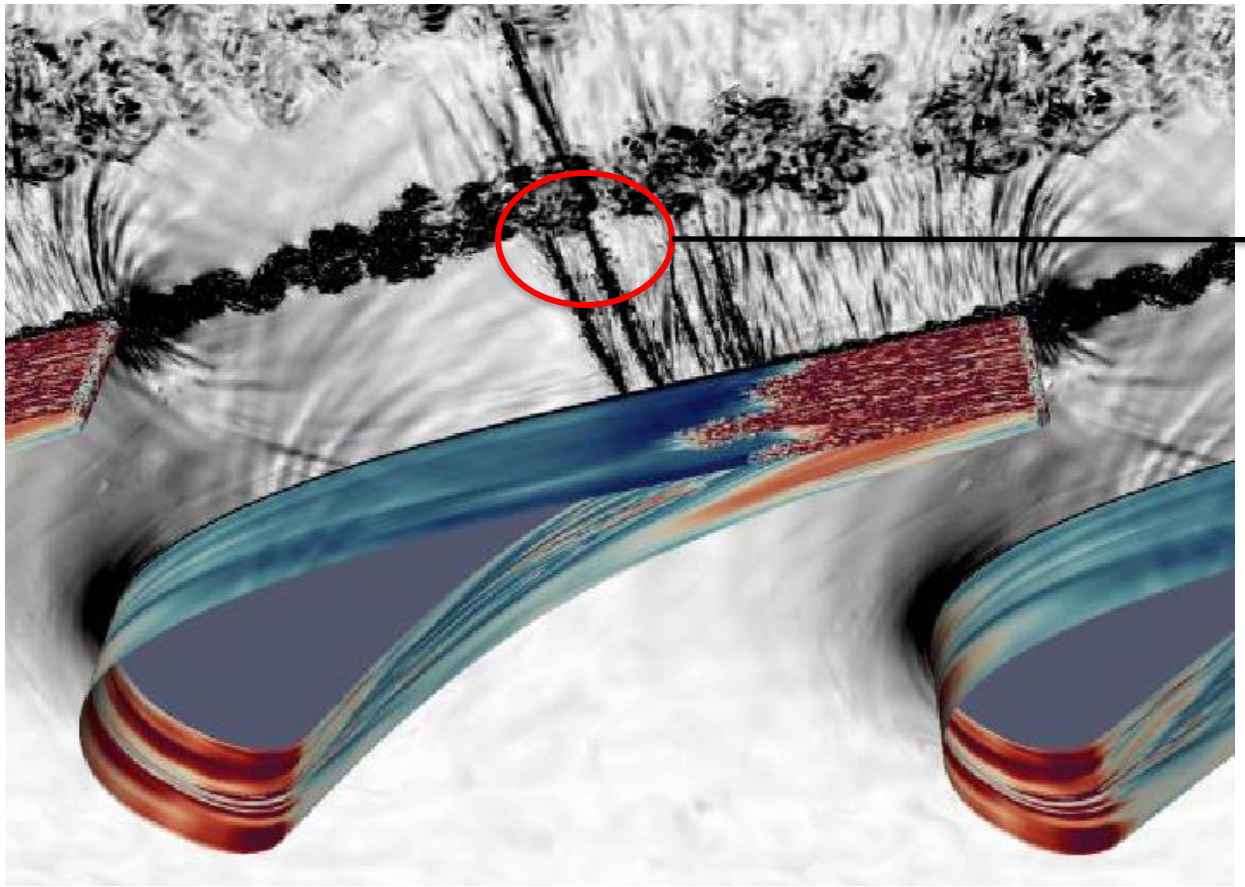
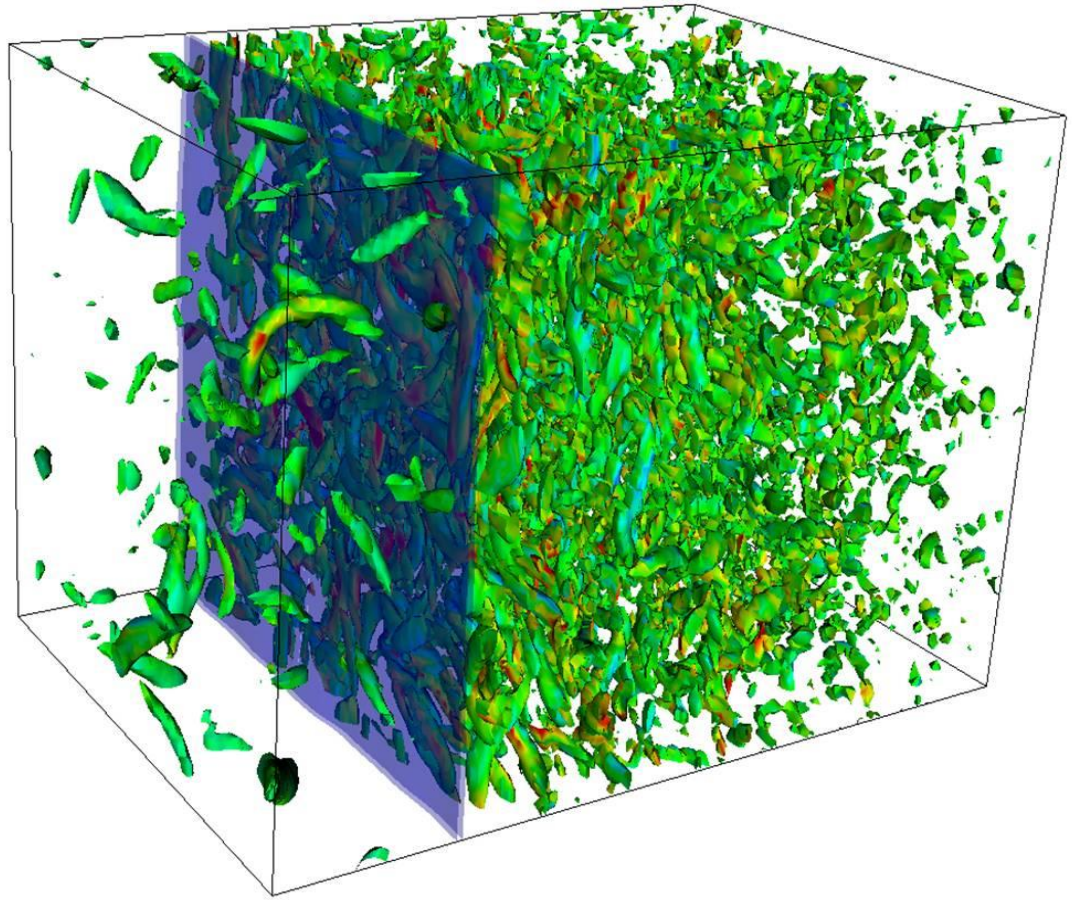
# Numerical methods for compressible turbulent flows

## *Ongoing improvements shock-capturing*





*Large Eddy simulation of the LS89 cascade @ VKI using ArgoDG*
*Courtesy Cenaero; collaboration Cenaero & VKI*

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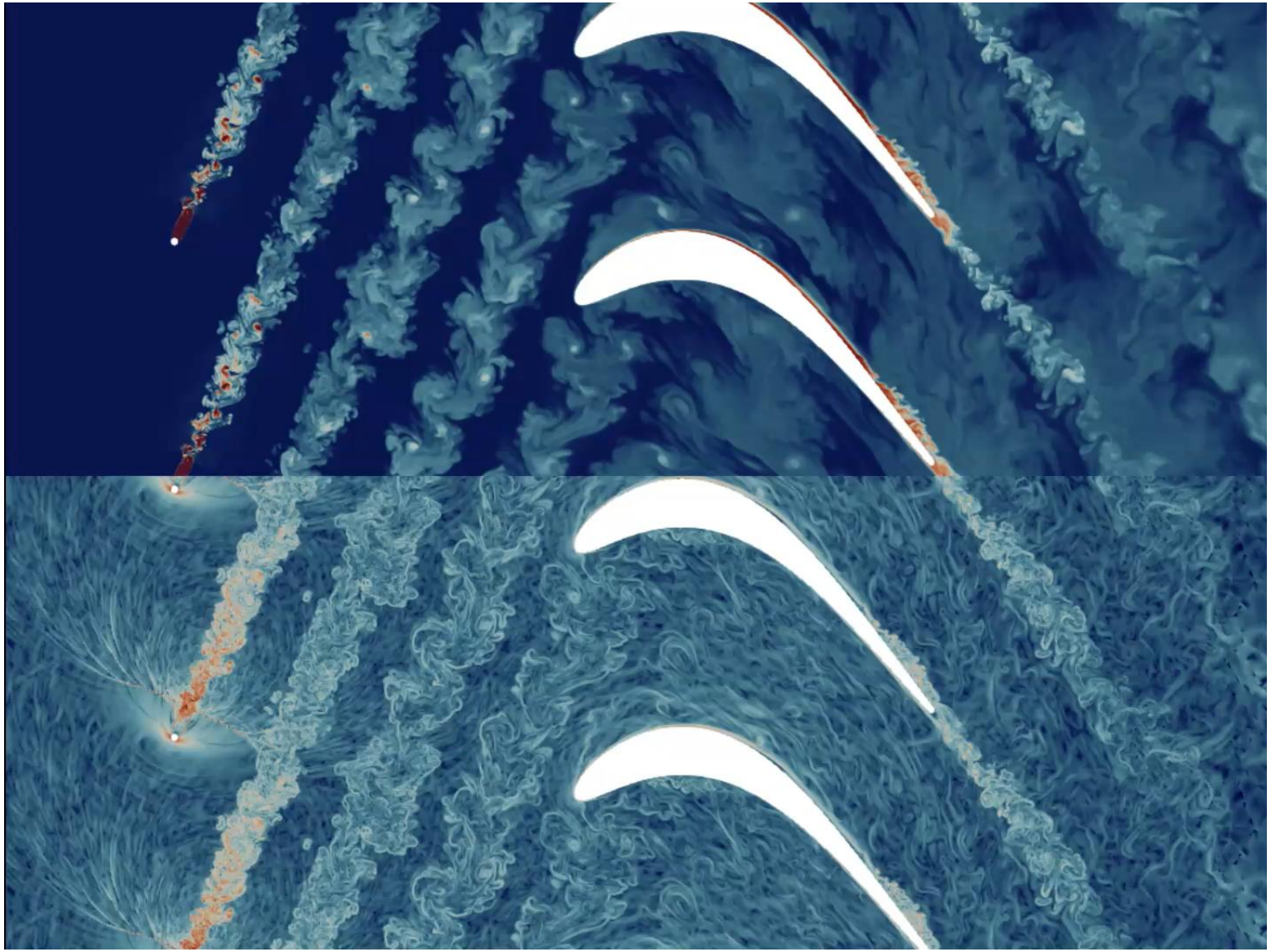
# Application to turbomachinery cascades

*Spleen LPT cascade parametric study*

- Spleen data set @ VKI
- Study of Mach & Reynolds effects on
  - Separation
  - Transition
  - Loss mechanism
  - Modal decomposition (G. Lopes 2025)
- High Speed LPT
  - Separation
  - Significant scale turbulence in wake
  - Compressibility / acoustic effects



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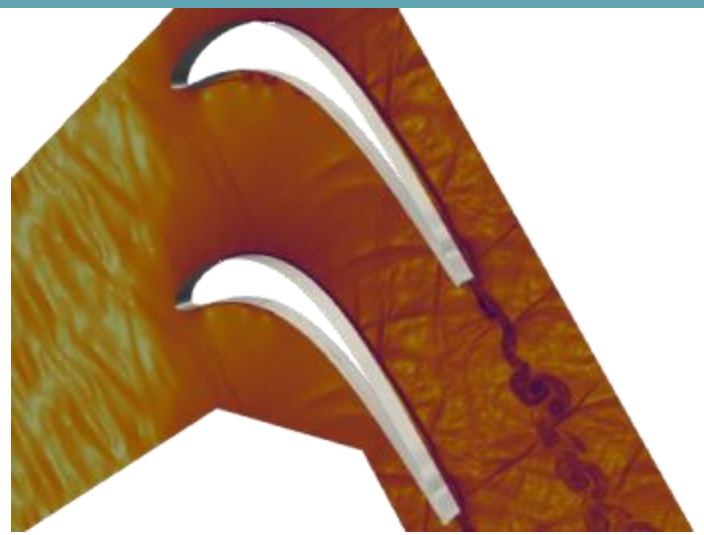
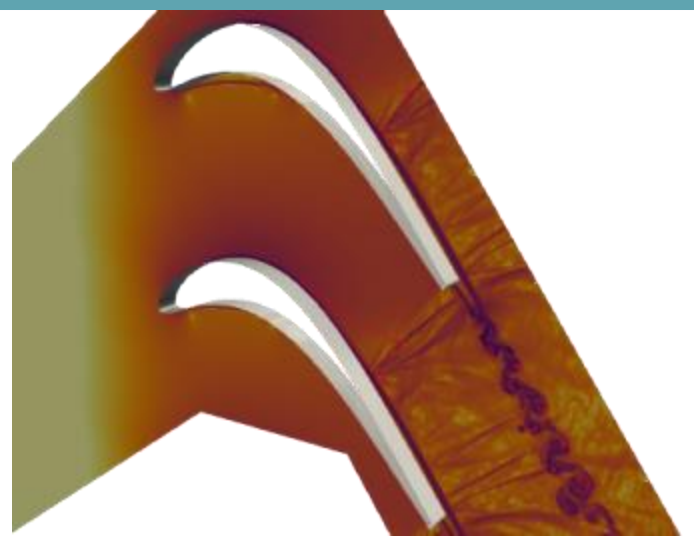
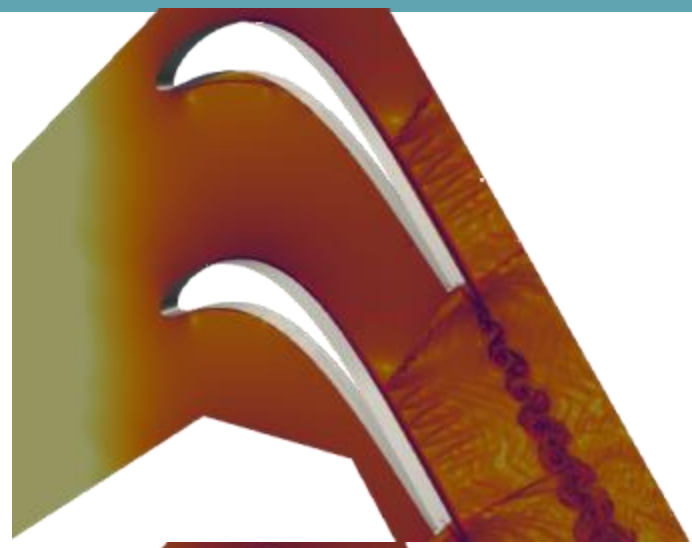
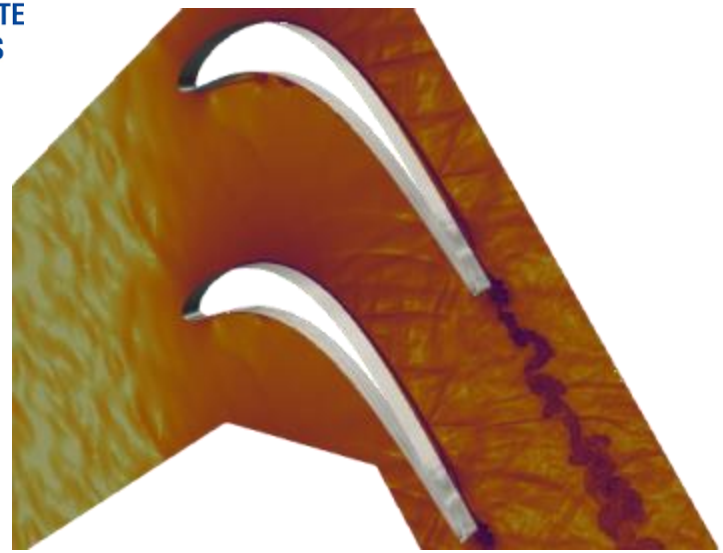
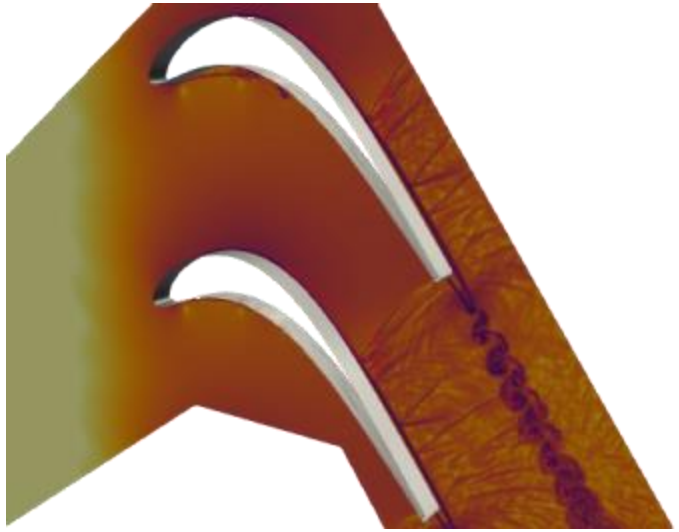
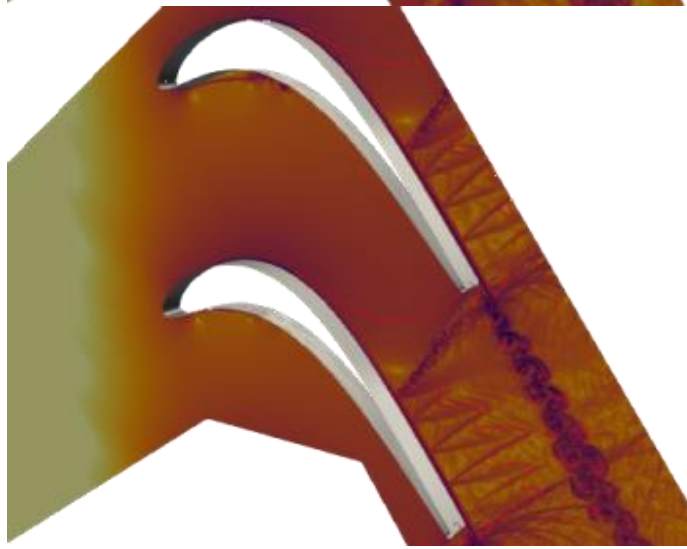
SPLEEN

# Application to turbomachinery cascades

*Spleen LPT cascade parametric study*

Re=70k

Re=120k

Subsonic (M=0.7)

Transonic (M=0.9)

Choked (M=0.95 .. 0.96)

# Integrating physical and virtual experiments

*Complementarity, challenges and synergies*

## Complementary tools

- Physical experiments
  - Large number of operating points
  - Realistic conditions
  - Intrusive measurements in few points
  - Measurement uncertainties / resolution / errors
  - Wind tunnel imperfections
- Virtual experiments (DNS/LES)
  - Few operating points
  - Reynolds number / geometric complexity limited
  - Non-intrusive measurements in all points
  - Exact data

## Synergies

- Validation of simulations by experiments
- Interpretation of experiments by simulation
- Complete datasets (on simplified geometries)
- **Improve measurement devices using simulations**
  - DNS attainable ~ low Reynolds and moderate complexity
  - Detailed flow field -> better calibration models
  - Conditions beyond calibration tunnel

## Why DNS and not (classically used) RANS ?

- Transition & laminar separation
- Shock boundary layer interaction
- Large scale turbulence interacting with boundary

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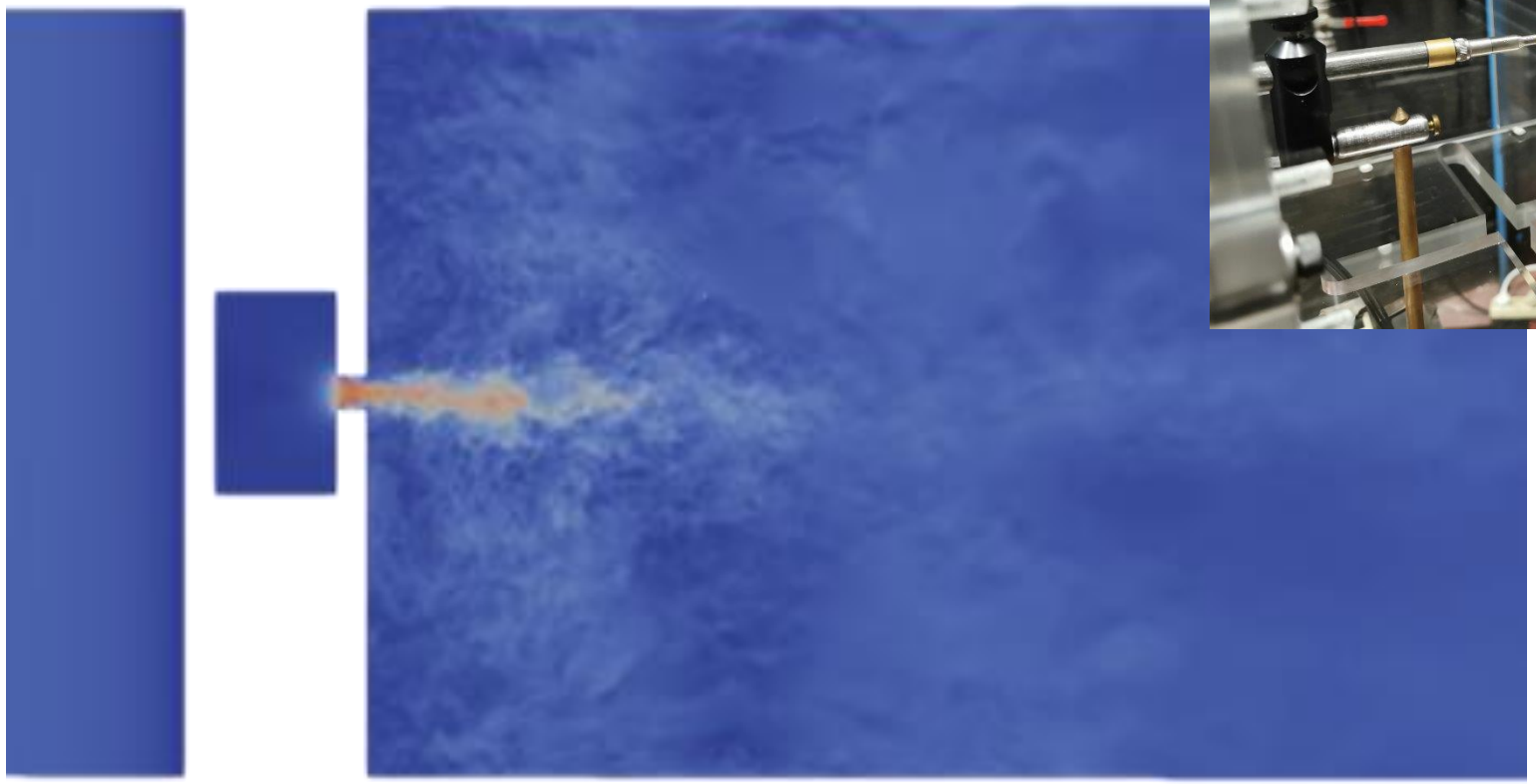
# Using DNS/LES to improve measurement devices

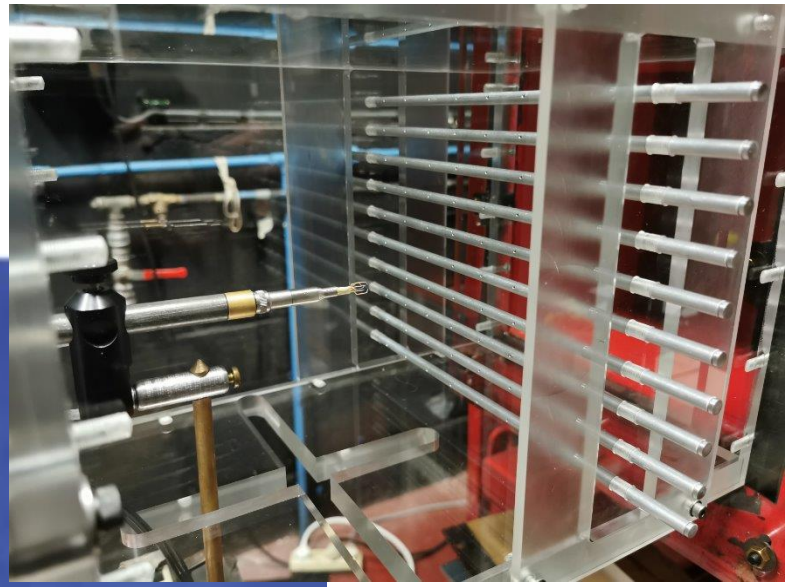
*Active turbulence grid (PhD F. Bertelli, VKI / ULiège)*

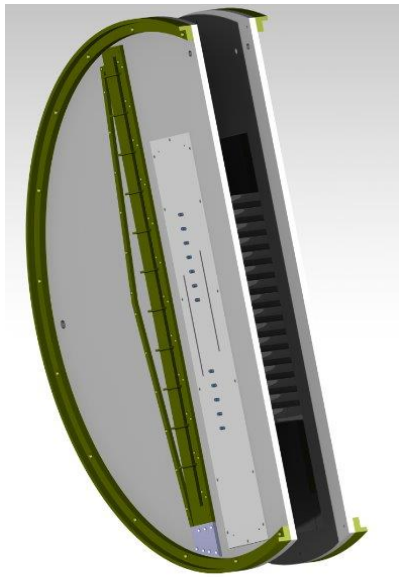
Design: independent control of turbulence

- Intensity
- Length scale

PoC LES -> DNS computations to understand Coanda, … effect







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# Design of military grade distortion grids

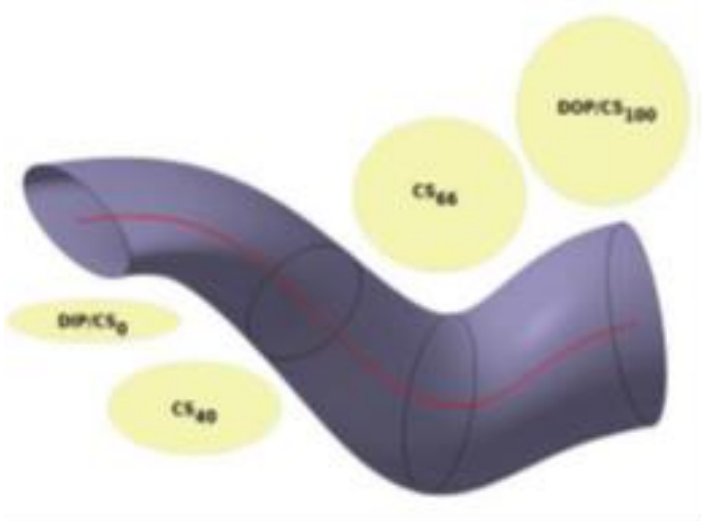
## *DEFRA "Next Generation Combat Aircraft Technologies" Costeo project*

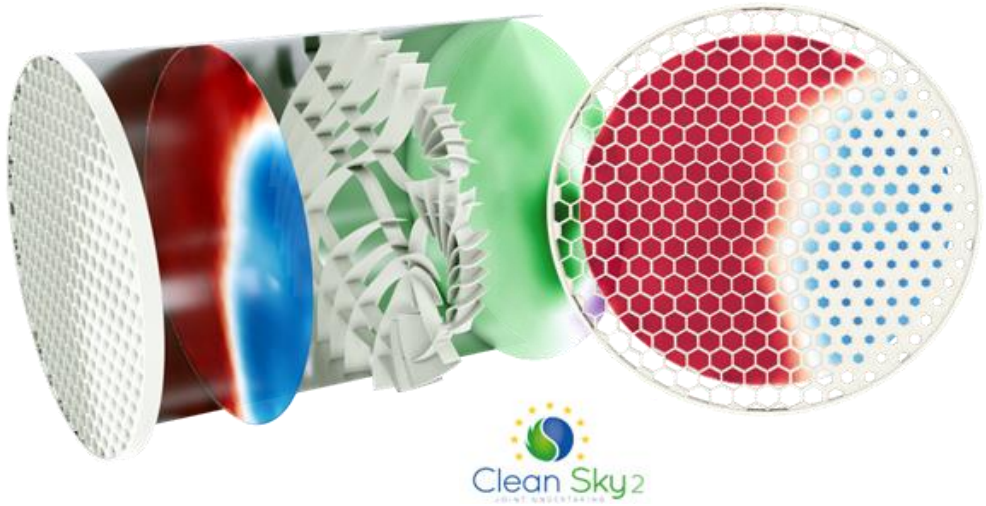
- *BeCover*, SAB, VKI, Cenaero, ULiège*
- *Reproduction distortion on military engine on test bench @ BeCover*
- *Collaboration w/ Cenaero on distortion grid design*
  - *Hybrid RANS-LES simulation to characterize distortion at AIP*
  - *DNS : database of graded aerodynamic material for total pressure and swirl distortion (~ Astoria)*

DEFRA
DEFENCE-RELATED RESEARCH ACTION

BeCOVER

Cenaero




*CleanSky project "Astoria" (SAB/Cenaero/VKI)*

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# Investigating multihole probes in low-Re high-Mach regimes

*PhD A. Reuter (ULiège/VKI)*

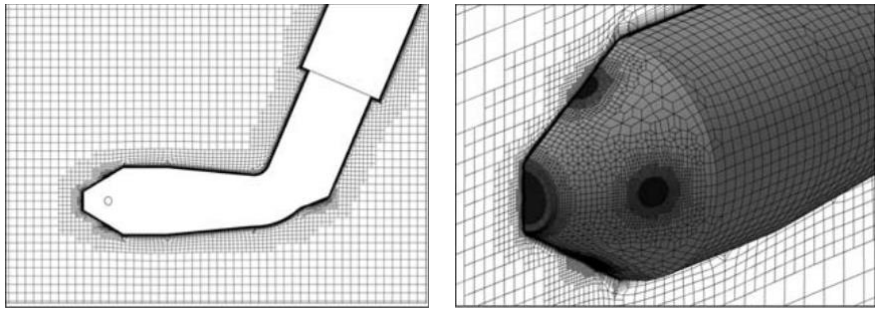
Measures direction, velocity, total pressure

Measurement chain errors / limitations

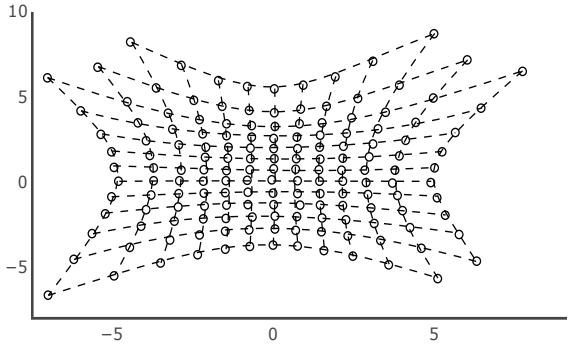
- Transducer resolution
- Frequency response

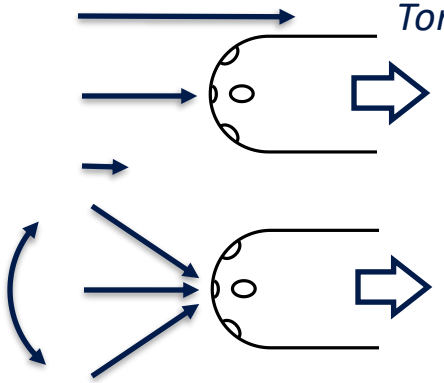
Epistemic uncertainties / errors

- Intrusivity
- Shear flow ~ probe size
- Upstream large-scale turbulence
- Oscillating shock structures probe
- Vortex shedding probe



*Torre (2023), RANS simulation probe*



Research epistemic errors using detailed DNS and measurement chain characteristics

- Correct calibration or quantify uncertainty
- Extrapolation outside of calibration range
- Robustify design

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# Concluding remarks

## Conclusions

- Complementarity physical and virtual experiments for understanding flow, improving models, …
- Need to bring both closer together by solving setup / measurement / … issues
  - Simulation : improving discretization techniques, turbulence injection, …
  - Measurements: finer control on inlet conditions, improved calibration, end-wall effects & AVDR
- DNS/LES for studying operation and design of experimental devices
  - feasible with current numerical methods and computational power
  - Reynolds-averaged Navier-Stokes put out of comfort zone (laminar separation, transition, large scale turbulence, shock buffeting, …)

## Started recently

- Distortion generators (DEFRA NGCAT project Costeo)
- Multihole pressure probe calibration

## Planned later

- Rarefaction and compressibility effects on hotwire
- Turbulence grids

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