Vers un écosystème unique en Wallonie pour l'innovation dans le secteur aéronautique

Recherche collaborative autour des futures architectures d'aéropropulseurs et opportunités dues à la création de BeCover

Liège Créative, 10 novembre 2023

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Design of Turbomachines

***Koen Hillewaert**, Design of Turbomachinery and propulsors - ṗ*
Sr. Research Engineer @ Cenaero, Associate Professor TU Dept. @ VKI

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***Loic Salles**, Mechanical aspects of turbomachinery and aerospace propulsion*

Towards increased efficiency of the propulsion system

Important challenges due to increased bypass ratio and stage loading

- Jet engine
  - acceleration of high ingested air flow
  - reaction force -> thrust
- Overall efficiency = thermal x propulsive
  - thermal efficiency: fuel -> kinetic energy
  - propulsive: kinetic energy -> thrust
- propulsive efficiency
  - loss: remaining kinetic energy in the air after aircraft passed
  - more efficient to accelerate little a large mass flow rate, since less loss of kinetic energy
- thermal efficiency
  - increasing pressure ratio of the cycle
  - increasing maximum temperature

South African Airlink Boeing 737-200 (source)
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Boeing 737 max (source),
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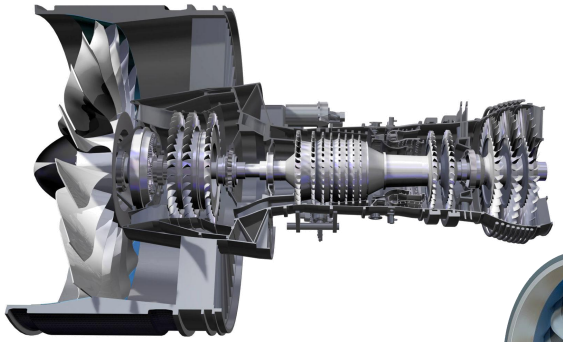
wChanges in jet engine architecture

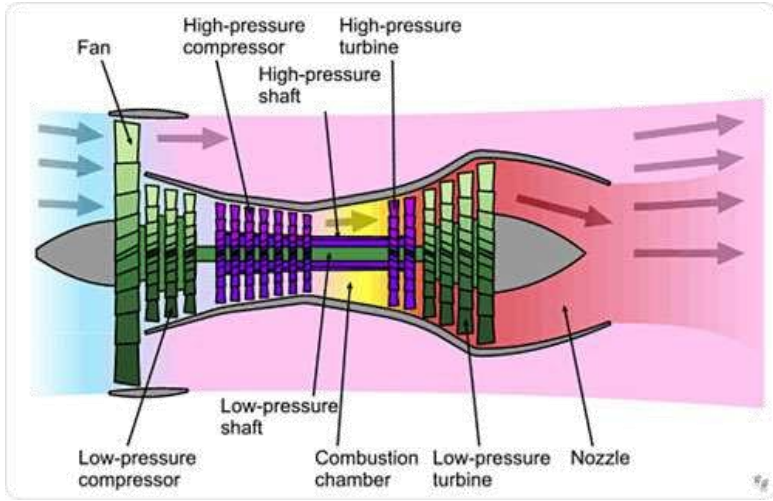
Increasing BPR while maintaining high/increasing stage loading

- turbofan
  - primary flow = gas turbine -> power, primary acceleration
  - secondary flow = high mass flow, small acceleration
  - bypass ratio = secondary/primary flow
- turbomachinery:
  - most compact/light machine ~ high flow rate
  - work ~ (blade speed)^2
  - rotation speed limit : slightly supersonic conditions at tip
  - weight ~ blade / stage count
- tendencies
  - higher bypass ratio
  - higher pressures
  - higher blade loading
- Geared turbofan

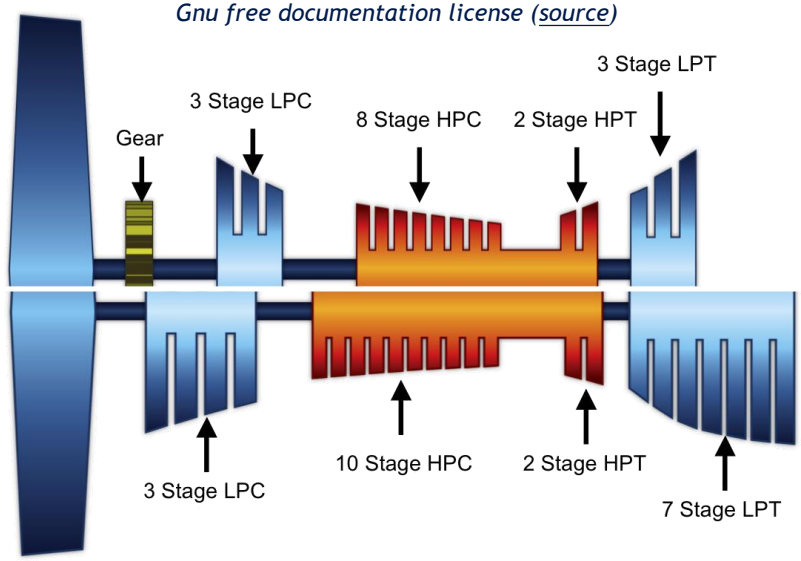


Geared turbofan (PW1100)
source: Pratt & Whitney web site

Classical turbofan (CFM Leap)
source: CFM website



Generic non-mixed turbofan layout
Gnu free documentation license (source)



Stage count classical (CFM LEAP/below) vs geared turbofan (PW1100g/above) for A320neo - Source: Pratt & Whitney web site

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Radical changes in engine architecture

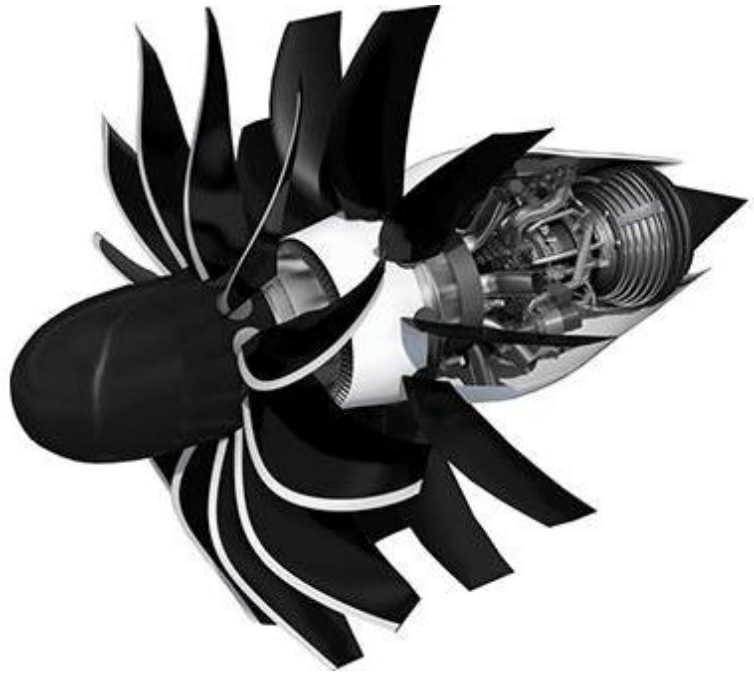
Unducted fan "CFM Rise" developed partly @ Safran

New architectures -> challenging aerodynamic regimes for simulations

- LPC & LPT : transonic/supersonic flow density / transitional flows
- transonic propellers (!)
- highly loaded stages
- ever more complex flow paths
- distortion of the flow entering into the engine

Requires improvements in simulation and understanding of flow

- turbulence models
- adaptation of simulation strategies
- robustness, convergence and accuracy
  - in challenging conditions
  - for "bad geometry" during optimisation
- low computational time since used for evaluating many variants at different operating points
- strong validation with respect to experiments and engine tests !



CFM Rise unducted fan - LPC/MPC at SAB
Source: Safran corporate web site

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A promising ecosystem for turbomachinery research

Industry

- **Safran Aero Boosters** : design and manufacturing of low pressure compressors for aircraft engines
- **Becover** : testing for complete compressor/fan modules at full scale including altitude effects
- **Pôle Skywin**

Complementary fundamental research competences and facilities, education

- **ULiège: numerical research, education**
  - development of high accuracy numerical techniques
  - fundamental analysis of turbulent flows in turbomachinery and measurement devices
  - simulation of turbomachinery vibrations including non-linear mechanical effects
  - MSc Aerospace engineering, PhD
- **Cenaero: industrialisation of simulation techniques and optimisation**
  - optimisation techniques using numerical simulation
  - industrialisation of accurate numerical techniques for DNS and LES
  - reference data for turbulence model validation
- **von Karman institute: experimental and numerical research, education**
  - detailed experimental studies of turbomachinery flows in exceptional turbomachinery rigs
  - probe development and calibration
  - model development, correlations
  - Research master in Turbomachinery, PhD

Computational resources:

- tier-1 lucia @ cenaero, available for academia via CéCi; lupi
- tier-O lumi @ CSC Finland, available through open calls via Belgian participation in lumi consortium
- open calls for computational resources in EU: EuroHPC, PRACE

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CÉCI

Lucia tier-1 supercomputer @ cenaero
source: Cenaero institutional web site

Lumi tier-0 supercomputer @ CSC
source: CSC institutional web site

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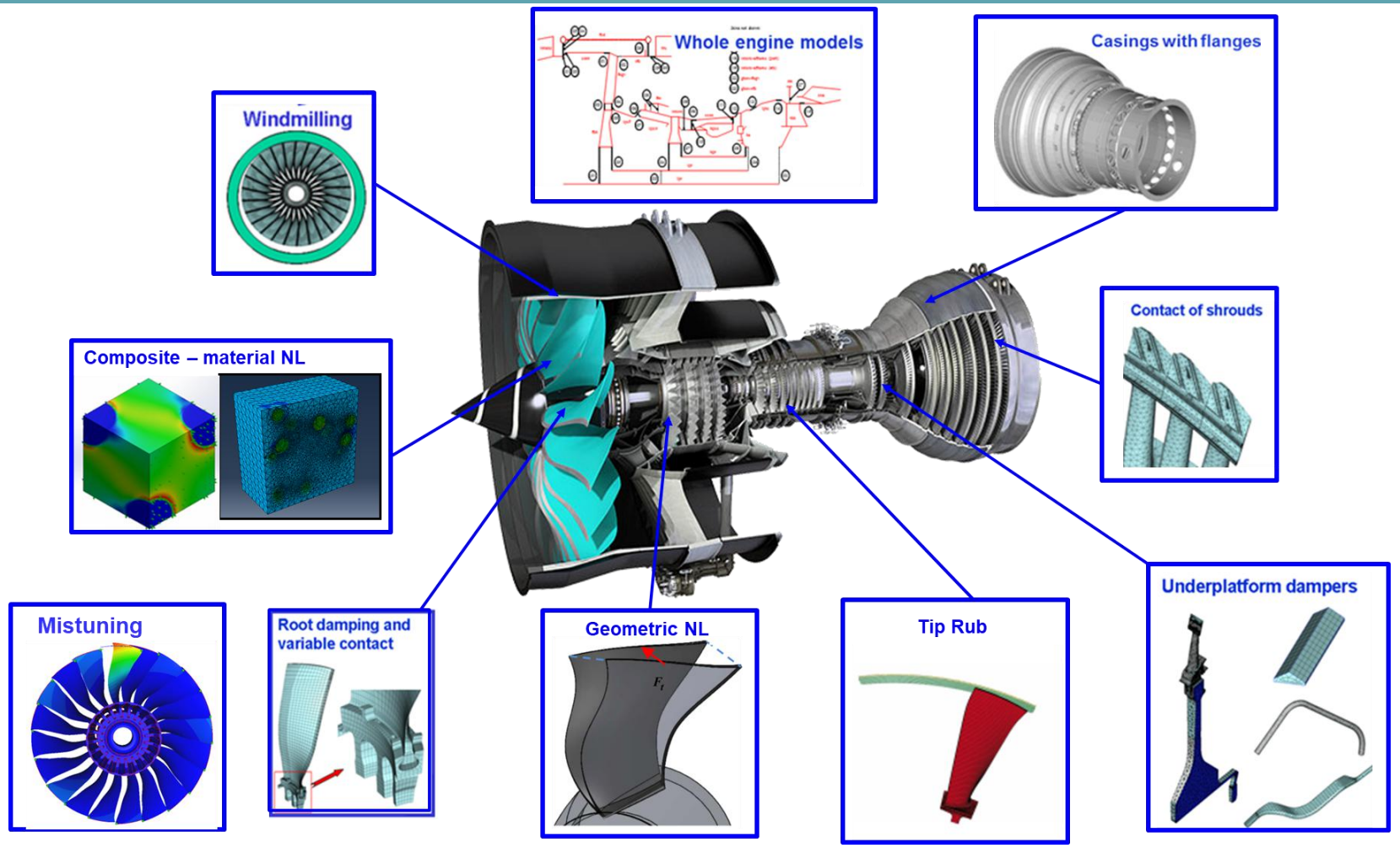
Mechanical aspects of turbomachinery and aerospace propulsion

Computational vibration



- A&M: Space structures and systems (G. Kerschen), Non-linear computational mechanics (J-P. Ponthot)
- 2024 - Digital twin of the rotating part of the rig with BeCover, Cenaero & V2i
- Formation continue : vibration

A&M : Design of turbomachinery group

Research activities

- development of high accuracy numerical simulation tools w/ Cenaero
- development of turbulence models and wall models with Safran, Cenaero and UCLouvain
- detailed study of flows in turbomachinery passages w/ experiments at VKI
- quantitative analysis of turbulent flows and budget equations w/ Cenaero
- development of meridional flow strategies with MTFC team of Prof. Terrapon and SAB
- development of novel strategies for simulating inlet distortion with SAB, Cenaero

Education in collaboration w/ industry

- MSc aerospace engineering -> propulsion, turbomachinery operation, design & cfd techniques
- formation continue: simulation of turbomachinery flows

Close collaboration with Multiphysics and Turbulent Flow Computation (Prof. Terrapon)

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Design of Turbomachines

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Multiphysics and Turbulent Flow Computation

Aerodynamic simulation tools

Physics of flow in turbomachinery

Wall-modeled Large Eddy simulation of the Create IIbis compressor at ECLyon using ArgoDG; Courtesy Cenaero

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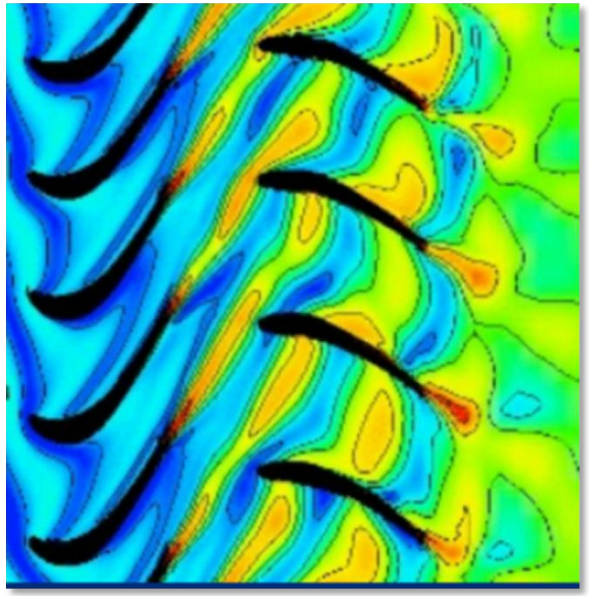
Cenaero

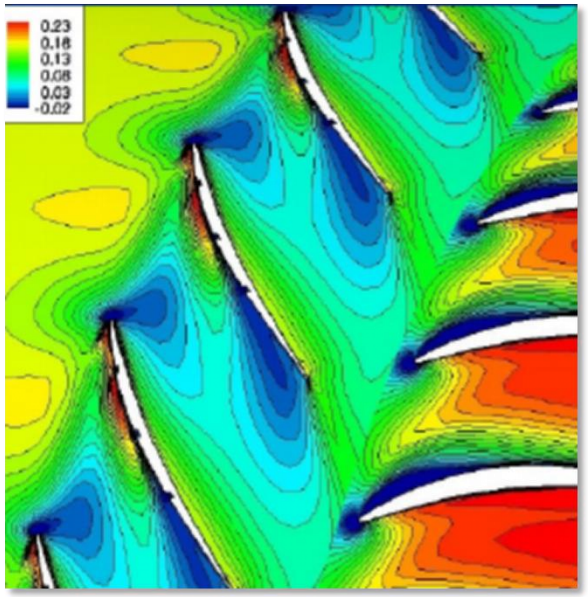
Aerodynamic analysis and design tools

Hierachy of simulation strategies inspired by Adamczyk's cascade

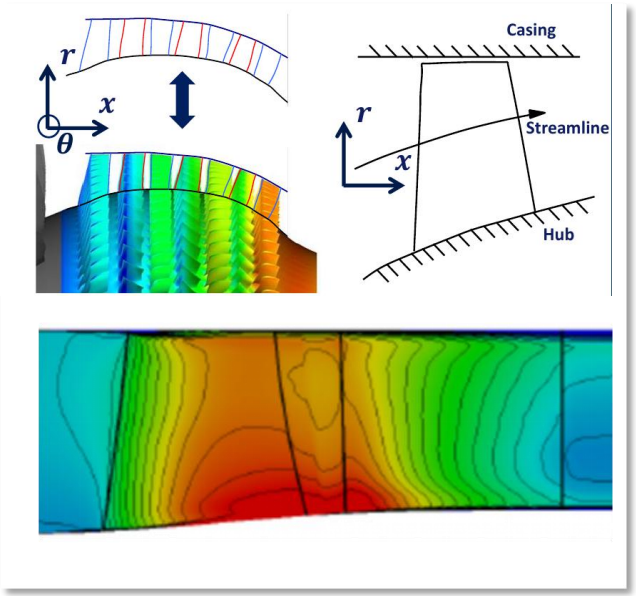
Scale resolving simulations
DNS, LES and Wall modeled LES
Months on O(10k)-(100k) processors
No or little modeling



Unsteady ensemble averaged flow
URANS (time or harmonic)
Weeks simulation on O(100) processors
Turbulence modeling



Ensemble averaged flow
RANS
hours simulation on O(10) processors
Rotor-stator interface



Pitchwise averaged flow
Meridional / Throughflow computations
minutes on O(1) processors
Blade force modeling

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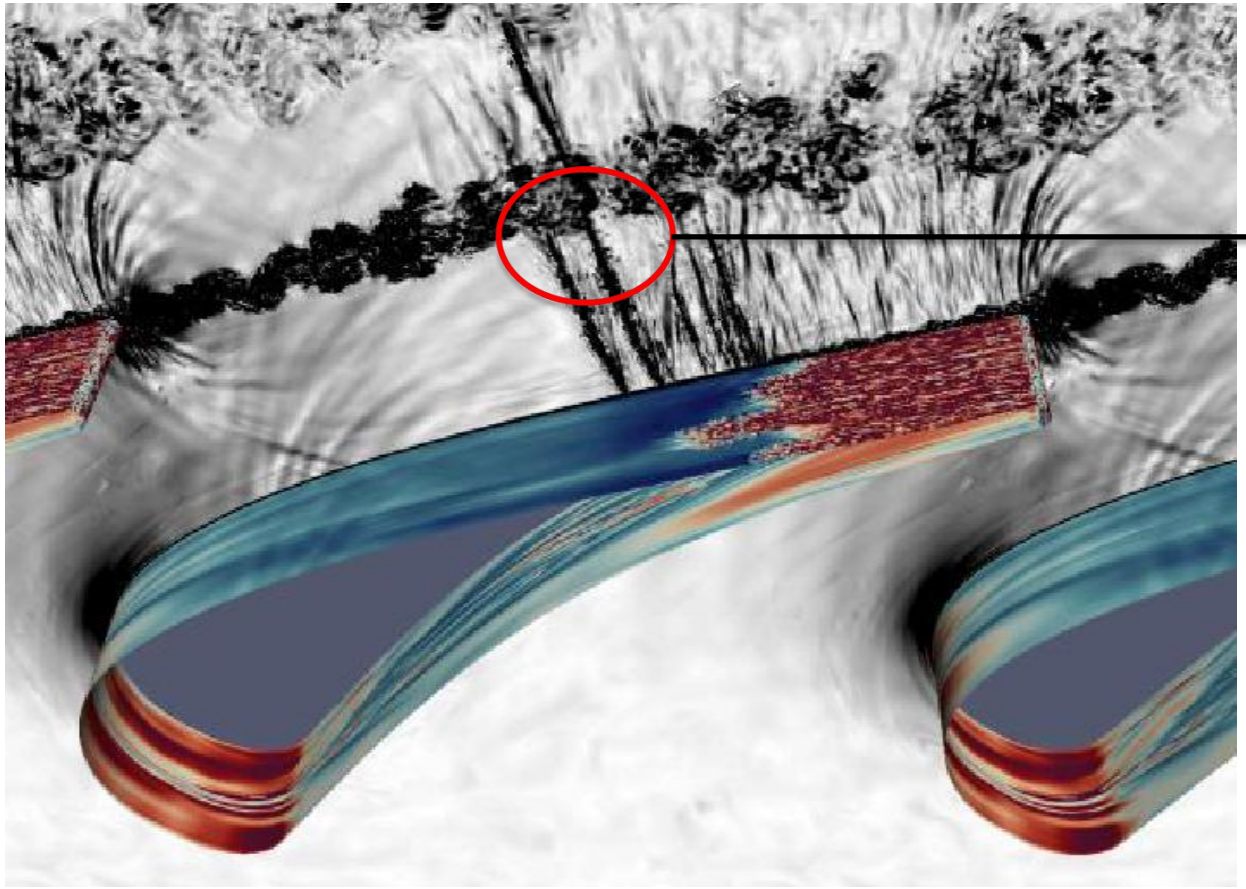
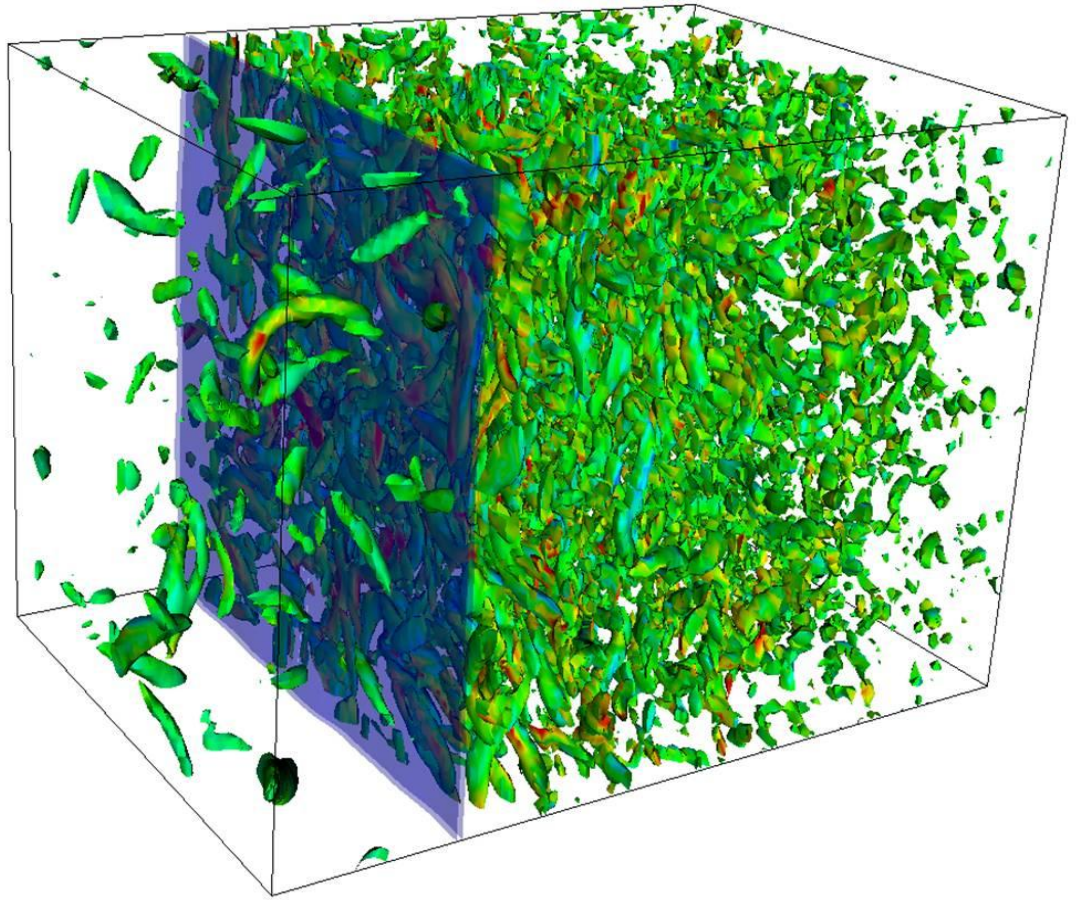
Aerodynamic analysis and design tools

Complexity of flow in turbomachinery passages - supersonic flows, shocks and turbulence





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

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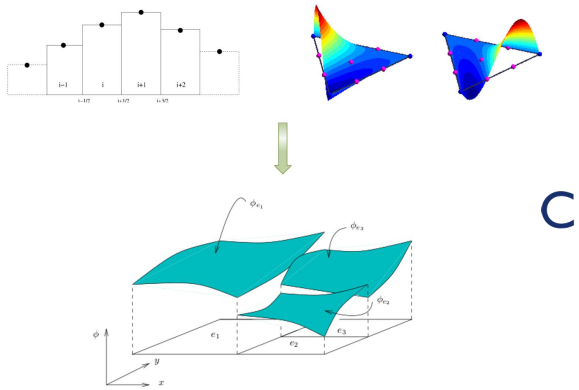
Aerodynamic analysis and design tools

Development of high-resolution simulation strategies (ForDGe/ArgoDG)

- Shock capturing for high order finite element fluid simulation
  - three way strategy for all Mach numbers -> hypersonics
  - quantify / minimise impact on turbulent budgets
  - fundamental development in ForDGe (A. Bilocq)
  - industrialisation in ArgoDG (M. Borbouse)
- Turbomachinery: using very precise DNS & LES
  - understand flow physics
  - improve turbulence models using reference data
- Collaboration MTFC, Cenaero
- BeCover: validate improved turbulence models for transonic conditions



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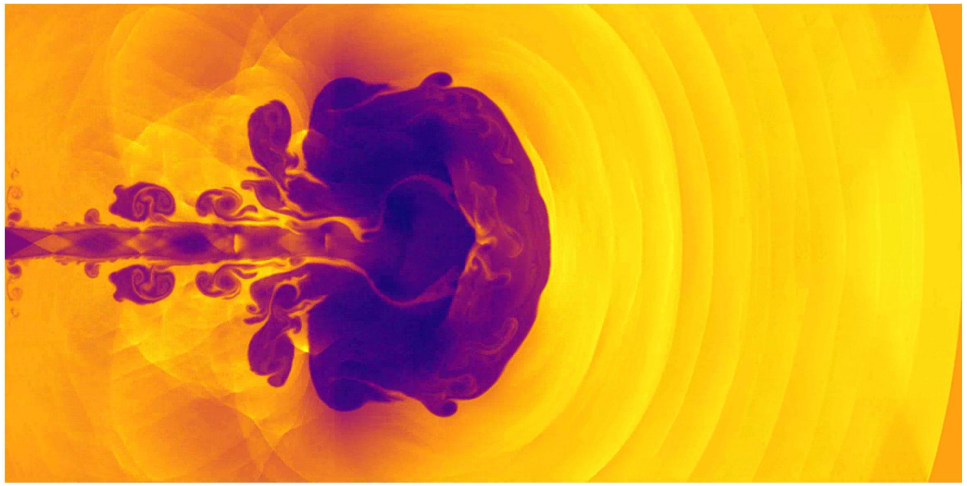
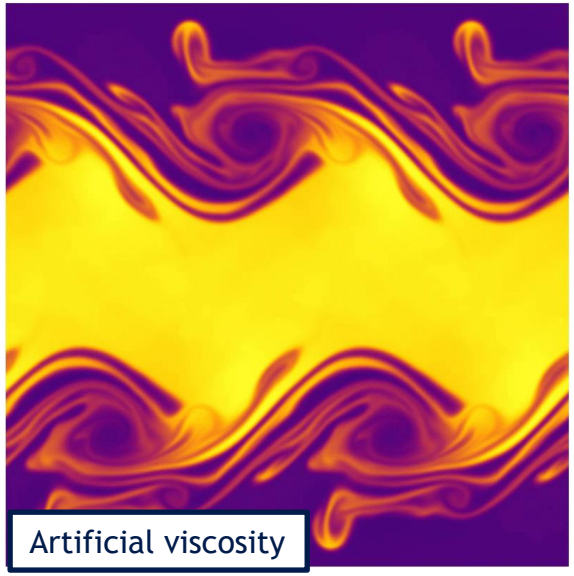
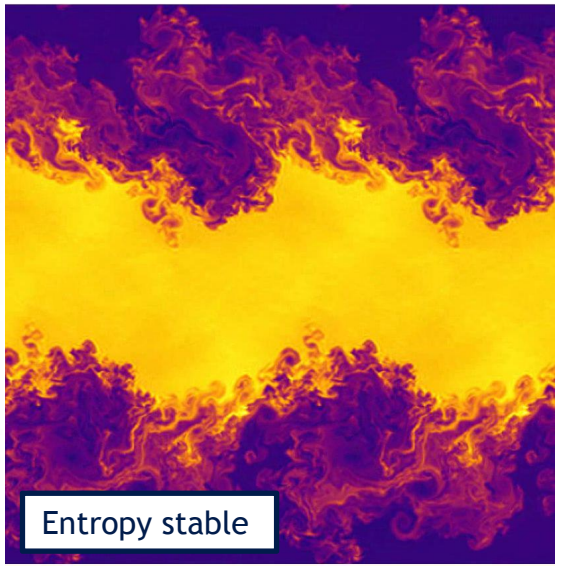
Development of High order discretisation (DGM) for flows







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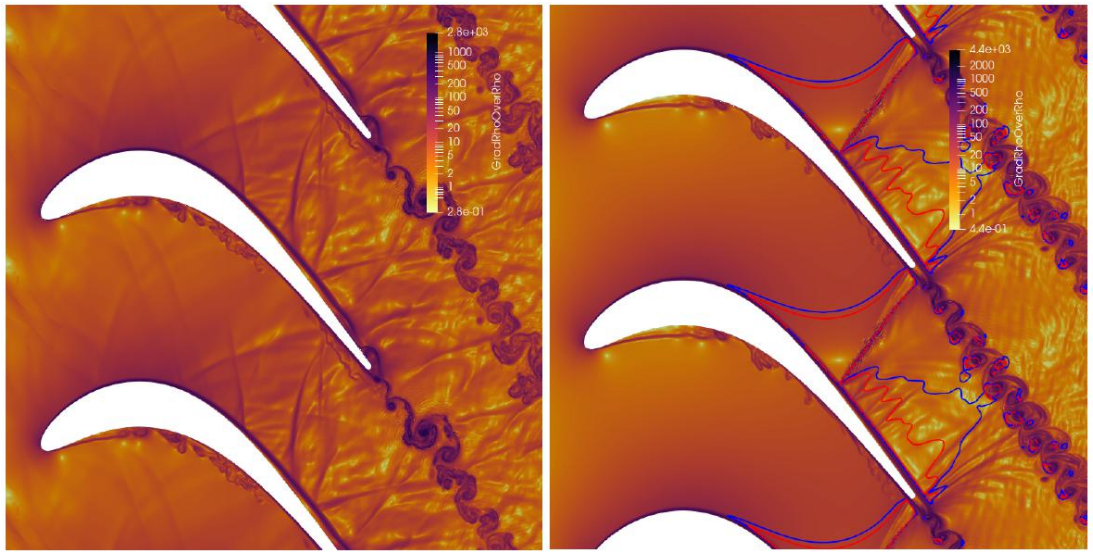
Impact of shock capturing strategies and improvement of methods - PhD Amaury Bilocq & PhD Maxime Borbouse (ULiège)
Supersonic jet (left) & Comparison of classical AV (middle) vs entropy stable (right) on compressible shear layer

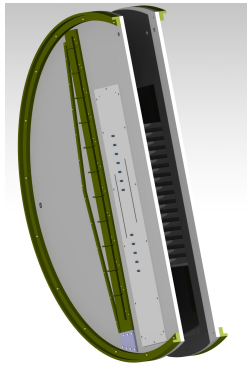
Aerodynamic analysis and design tools

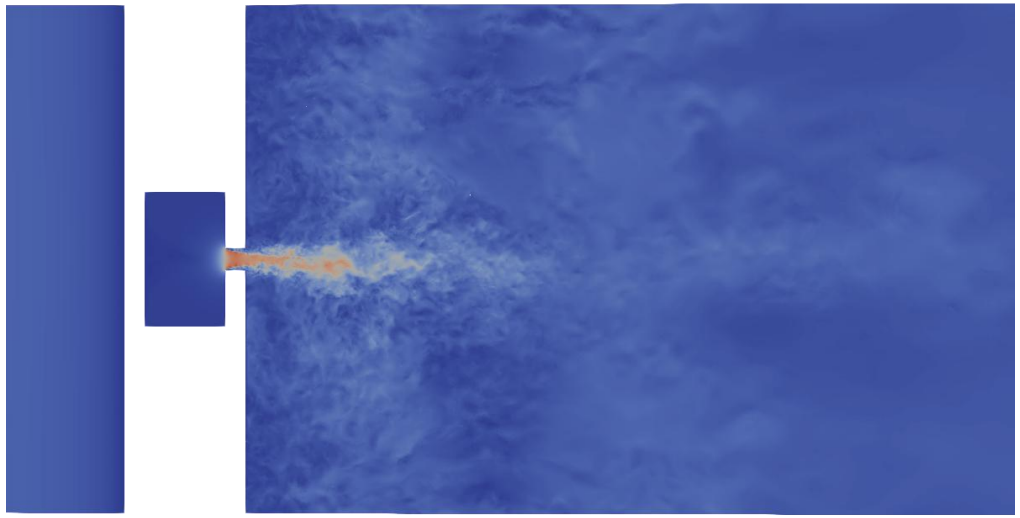
Simulation of (almost) all flow structures: DNS & LES (collab. Cenaero/VKI)

- DNS / LES for fundamental flows
  - resolve (almost) all flow structures
  - average over large time span to find average flow
  - first principle models
- Research using Cenaero's ArgoDG code
  - understanding turbulent flows in complement to experiments
  - developing/evaluating/calibrating turbulence models
  - improving precision of numerical techniques
- BeCover : probe development w/ VKI

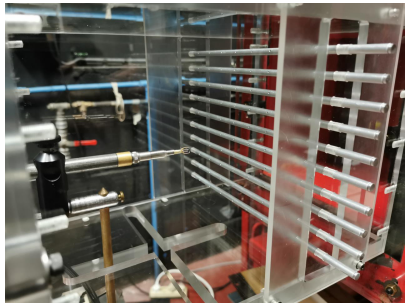


Ongoing DNS studies of transition and separation in a high-speed low-pressure turbine
Collab. PhDs M. Borbouse (ULiège) & G. Lopes (VKI/ULiège), Prof. S. Lavagnoli (VKI), Cenaero;
Data made available by Spleen CleanSky II project





Preliminary studies on flow mechanisms around active turbulence grid
Collaboration ULiège PhD F. Bertelli (VKI/ULiège), Prof. S. Lavagnoli (VKI) & Cenaero



Active turbulence grid experimental setup @ VKI
Collab. ULiège - PhD. F.Bertelli (VKI/ULiège)

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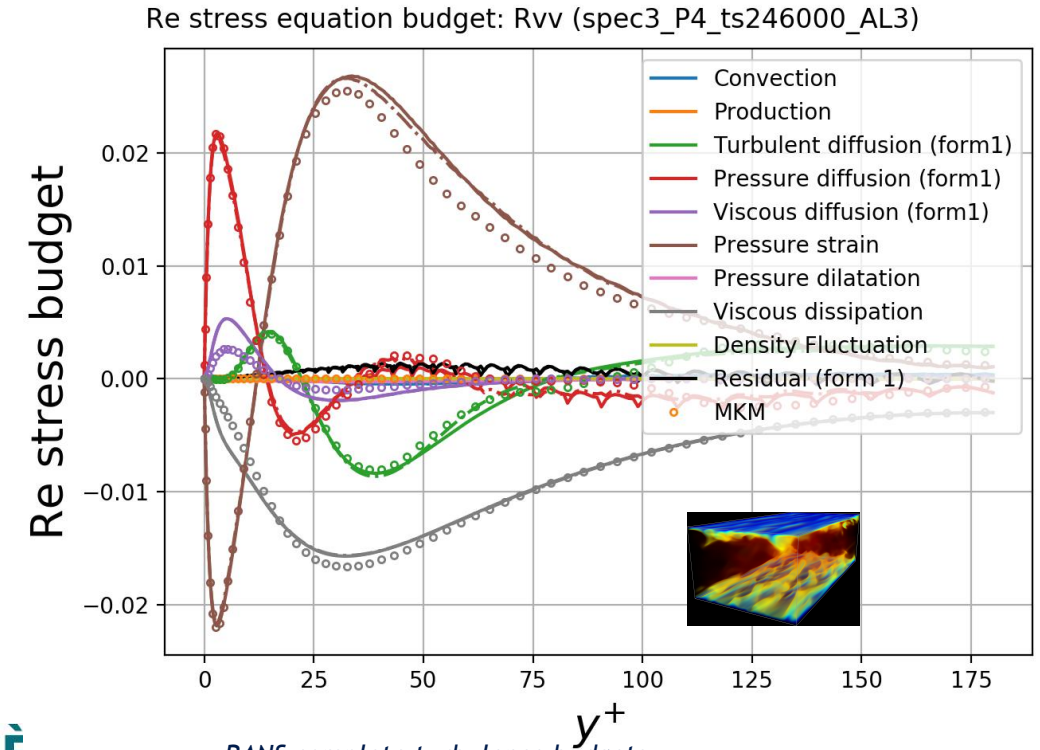
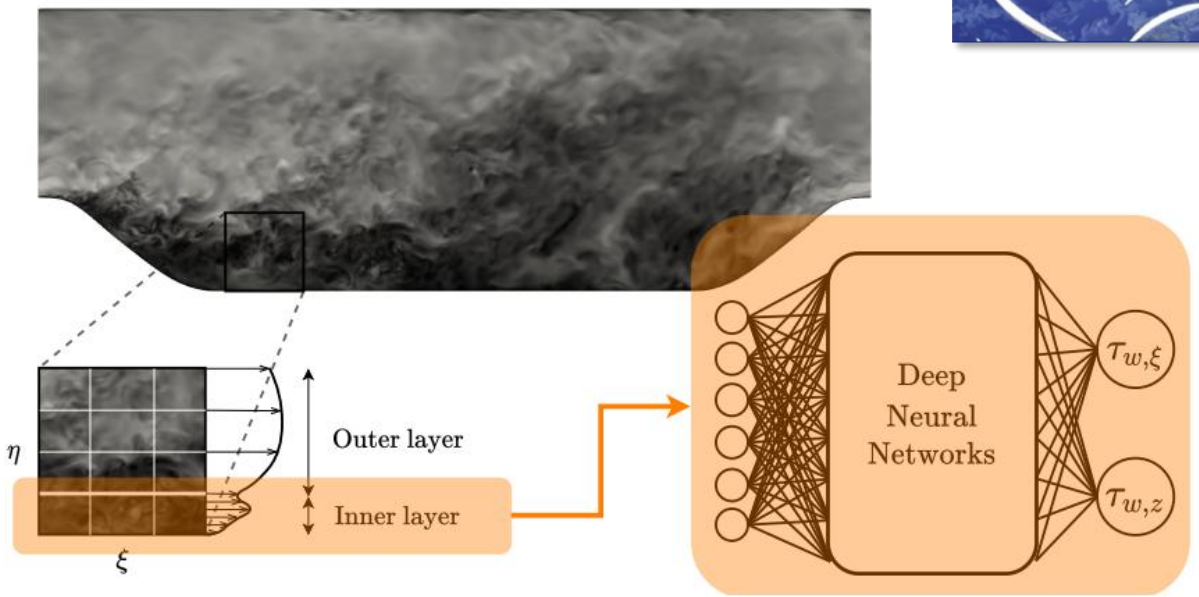
Aerodynamic analysis and design

Development of numerical techniques for turbulence modeling (collab Cenaero)

- Ongoing research
  - developing wall models for large Eddy Simulations
  - analysing turbulent transport terms resulting from averaging in RANS
  - analysing impact of numerical technique on closure of the budget
  - providing reference data for turbulence model



RANS complete turbulence budgets
Collaboration ULiège - M. Rasquin @ Cenaero



Machine learning for wall models
PhD Margaux Boxho (ULiège/Cenaero/UcLouvain)

Aerodynamic analysis and design

Unsteady RANS of off-design operation (collab. VKI)

- Approach
  - solve for ensemble averaged flow
  - impact of turbulence is modeled
  - unsteady flow fields
- Industrial work horse
  - steady/frequential used for aerodynamic/structural optimisation
  - study of instabilities, distortion of given geometry
- Collaborative research on distortion
  - *Cenaero/VKI: Generation of tailored distortion in wind tunnel (Astoria project)*
  - Impact of distortion on stability and performance (PhD R. Toracchio,VKI/ULiège)
  - Collaborative research (ULiège/Cenaero/VKI/BeCover) on simplified approaches fo integrating distortion in optimisation
    - mono-passage simulation w/ fluctuating boundary conditions
    - frequency domain approaches
- Becover
  - validation data for models (turbulence modeling, simplified)
  - support BeCover customers in analysing unexpected flow regimes

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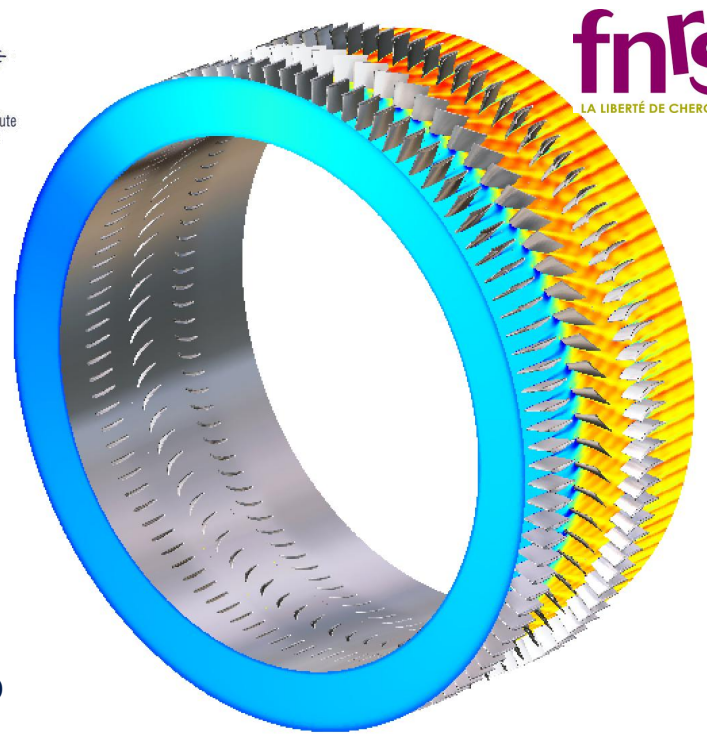

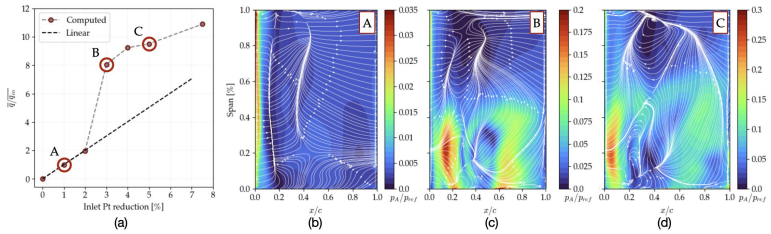

Study of the impact of distortion on performance, stability and risk of flutter for a LP compressor
PhD R. Toracchio (VKI/ULiège), F. Fontaneto (VKI)

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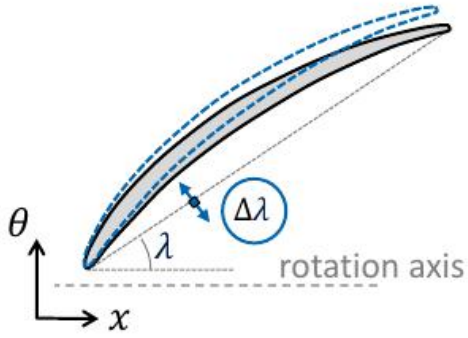
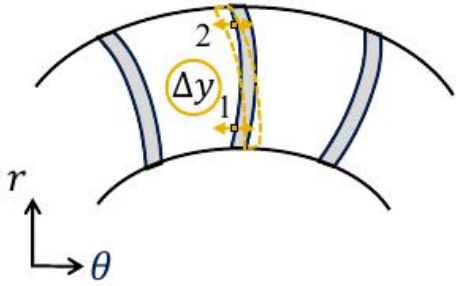
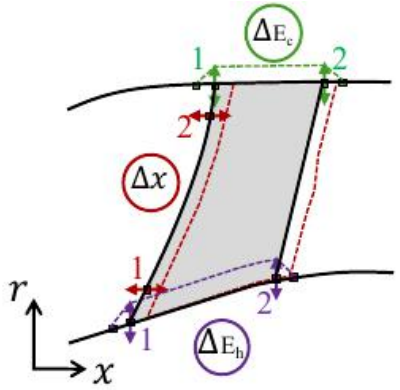
Aerodynamic design techniques

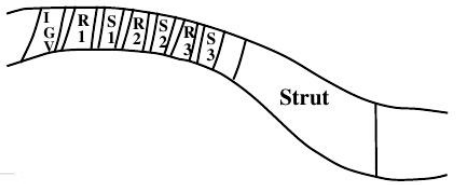
Throughflow design and analysis methods (MTFC ULiège & Safran)

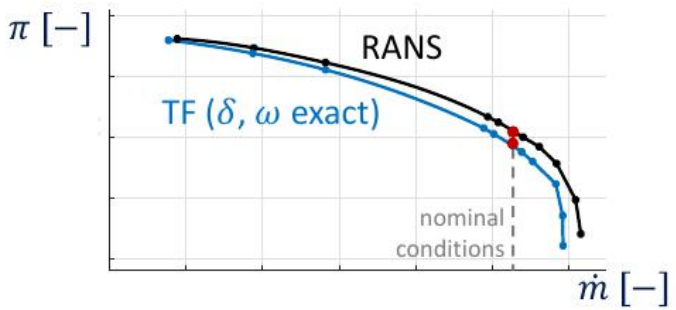
- Throughflow approach
  - average around axis
  - solve for tangentially averaged flow
  - fast estimation of operating curve
- Current (A. Budo, ULiège) w SAB
  - improvement of (geometrical) formulation
  - correlation data for profile performance ?
  - geometrical inaccuracy issues
- Future research axes
  - supersonic flows and shocks
  - distortion & mistuning
  - complex flow paths
  - integration in design loop
- BeCover : model validation

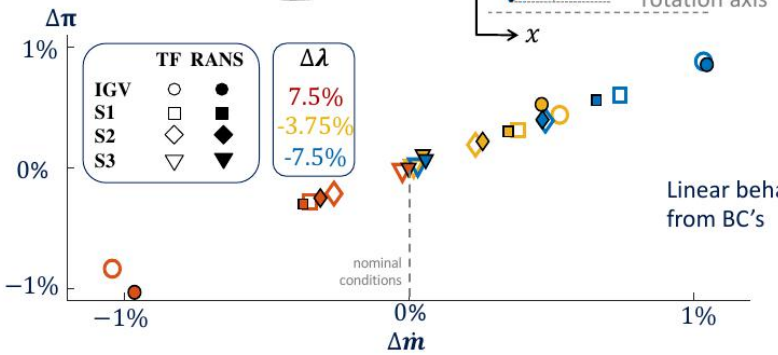


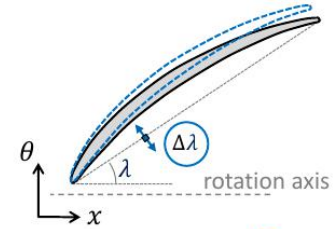












Predicting impact of geometric errors on blade geometry on performance using a throughflow method
PhD Arnaud Budo (ULiège) @ MTFC - Pr. V. Terrapon (ULiège)

Concluding remarks

- Design of LPC @ SAB, requires improvement of design tools, approaches and ultimately better understanding of turbomachinery flows
  - radical changes in engine architecture -> new flow regimes
  - high loading -> simulation tools used further away from “comfort zone”
  - high loading, inlet distortion -> increased risk of unstable operation
- Favorable situation in RW/Be for creation of a true pole of competence
  - High competence in turbomachinery design, development of numerical and experimental techniques
  - Complementarity research institutes, universities and industry with collaborations in place locally and internationally
  - Access to top facilities in experimental (VKI, BeCover) and numerical research (Lucia supercomputer)
  - High level education: VKI (Research Master, PhD) and ULiège (Aerospace Engg, PhD, FC) involving industry
  - Favorable position of the government: RW projects, Skywin, Wings, ...
  - ULiège involved in the fundamental development of numerical techniques and study of turbulence w. Cenaero/VKI
- Creation of a unique test facility in BeCover -> cover the entire spectrum of research activities
  - competitive advantage for walloon aeronautic industry
  - credibility to partake in tenders for high level research grants
  - momentum for increased collaboration in RW

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