Numerical and experimental study for the prediction of the steady, three dimensional flow in a turbine nozzle vane cascade using OpenFOAM

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Outline

- Who we are
- Motivation & background
- Experimental and numerical setup
- Results and validation against measurements
- Conclusions & future developments

Who we are

EST - Energy Systems and Turbomachinery Group
Department of Engineering
University of Bergamo, Italy

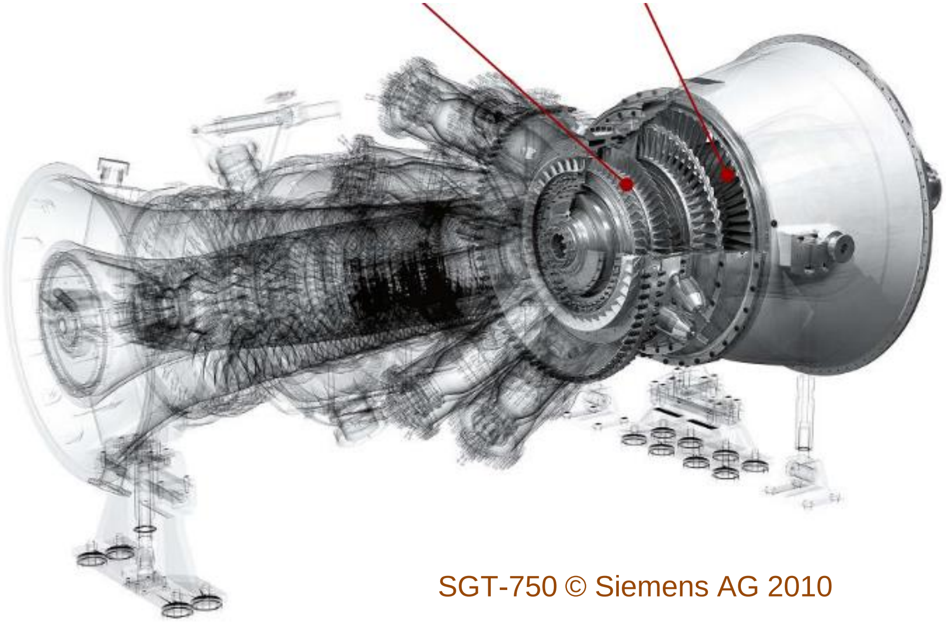
SCS Italy

CINECA

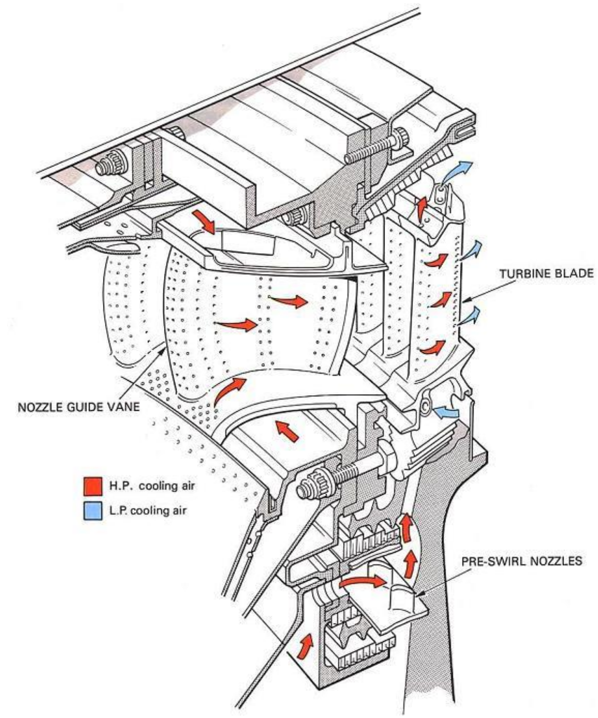
Motivation

Main goal: exploring the potential of the OpenFOAM Toolbox to characterize the HP turbine section of a gas turbine engine

Air-cooled HP Turbine   Un-cooled LP Turbine



SGT-750 © Siemens AG 2010

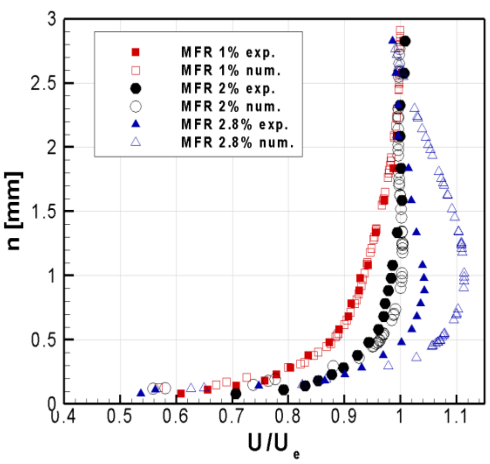


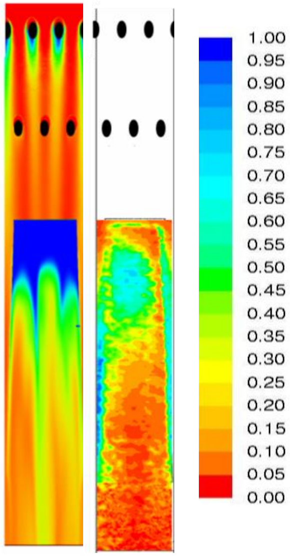
Background

Experimental and numerical investigation of thermal and aerodynamic performance of linear vane cascade

- National Research Projects (PRIN) and Industrial research contracts
- Simulations by means of commercial CFD codes

Suction-type, open circuit wind tunnel





Current activity

OpenFOAM

CFD modelling supported by experiments

HPC platforms for CAE applications:
http://www.fortissimo-project.eu/
http://www.prace-ri.eu/

CFD open-source technology for industrial applications

Experimental setup

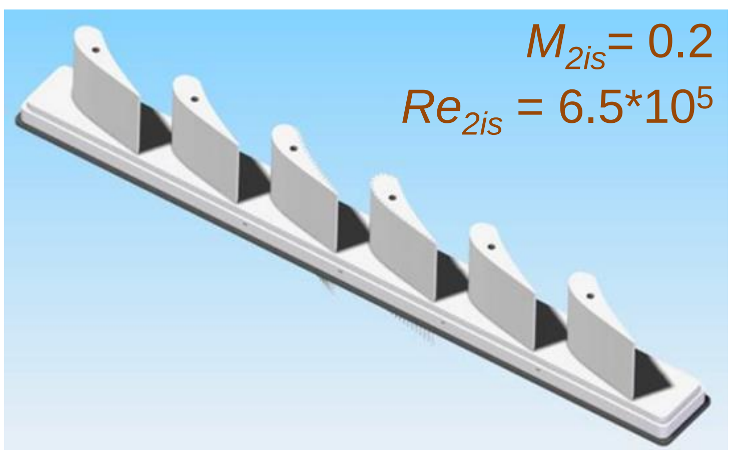
Solid Vane

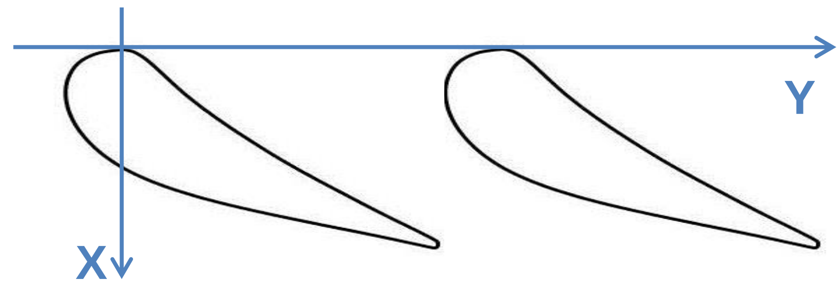
- c = 142.1 mm
- s/c = 1.04
- H = 98 mm
- H/c = 0.69
- β_2 = 70°
- β_1 = 0

Operating conditions

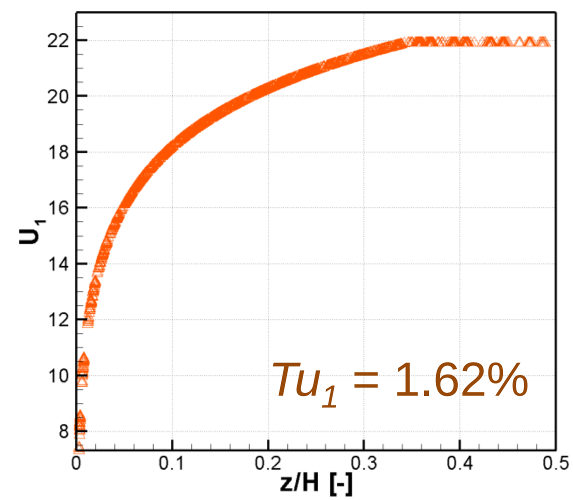
M_{2is} = 0.2

Re_{2is} = 6.5*10^5



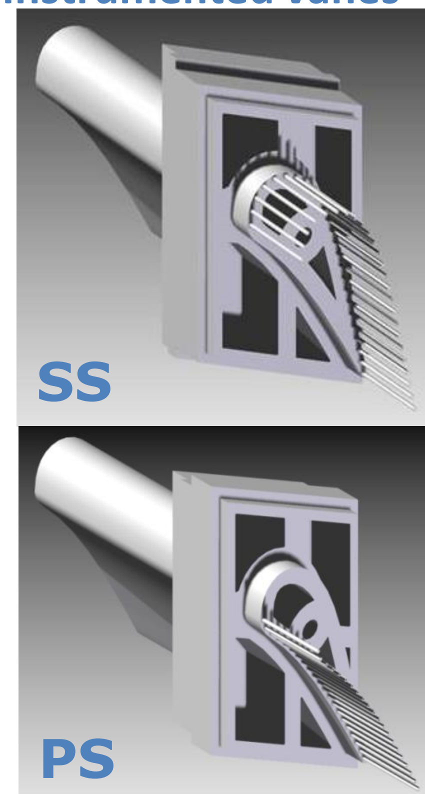


Inlet boundary layer (X/c_{ax} = -1.6)



Experimental setup

Instrumented vanes



Experimental data used for validation:

- vane loading at midspan (z/H=0.5)
- wake total pressure P_{t2} (z/H=0.5, x/C_{ax} = 1.50)
- kinetic energy loss coefficient ζ (at x/C_{ax} = 1.53)

$$\zeta = \left(1 - \frac{U_2^2}{U_{2is}^2}\right) * 100$$

5-hole probe

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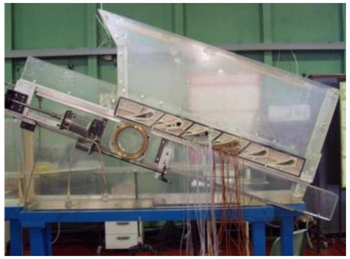
Numerical workflow

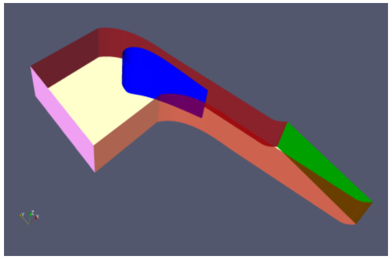
PRE-PROCESSING | **COMPUTING** | **POST PROCESSING**

PHYSICAL



MODEL

COMPUTATIONAL

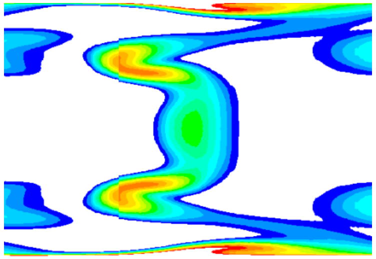


MODEL

SOLVING

HPC ENVIRONMENT

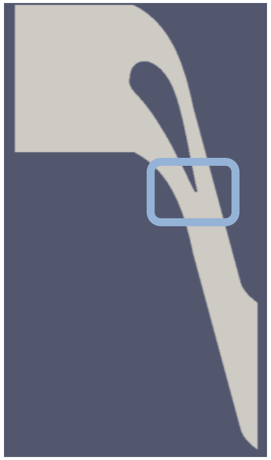
VISUALIZATION

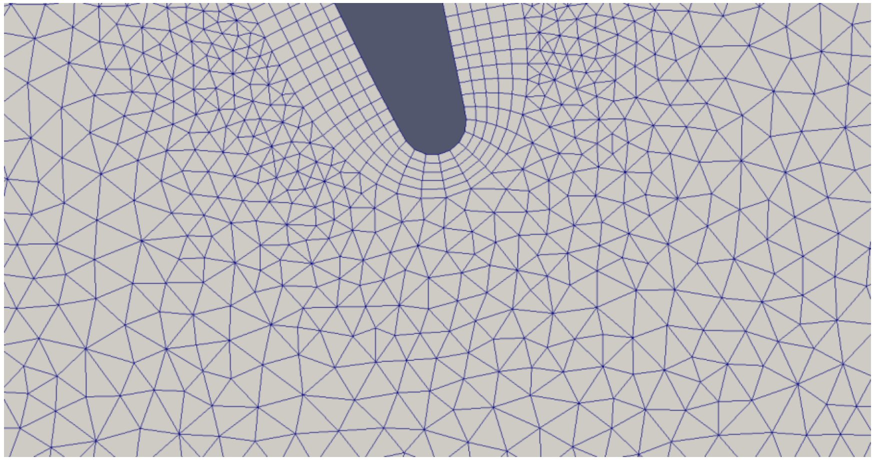


RESULTS

Meshing

– Meshing CAD geometry
– Criteria: *checkMesh* output & experimental fidelity
– Hybrid mesh topology
– SW: Pointwise (Pointwise Inc.)





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Mesh details

Different meshes were created to assess the sensitivity of the solver setup to the spatial discretization:

	TOPOLOGY			QUALITY				SIZE
Mesh name	y^+ (min – max – average)	BL hexahedra block	BL – # of layers	Max Non-orthogonality	Average Non-orthogonality	Max Skewness	Max Aspect Ratio	# of cells [Millions]
$hybrid_1$	15.1 – 113.7 – 60.2	yes	5	43.2	6.1	0.7	6.2	1.6
$hybrid_2$	15.2 – 116.8 – 59.7	yes	5	37.1	6.1	0.7	6.4	2.4
$hybrid_3$	**8.0 – 68.0 – 36.1**	**yes**	**5**	**36.9**	**6.2**	**0.6**	**4.6**	**3.5**

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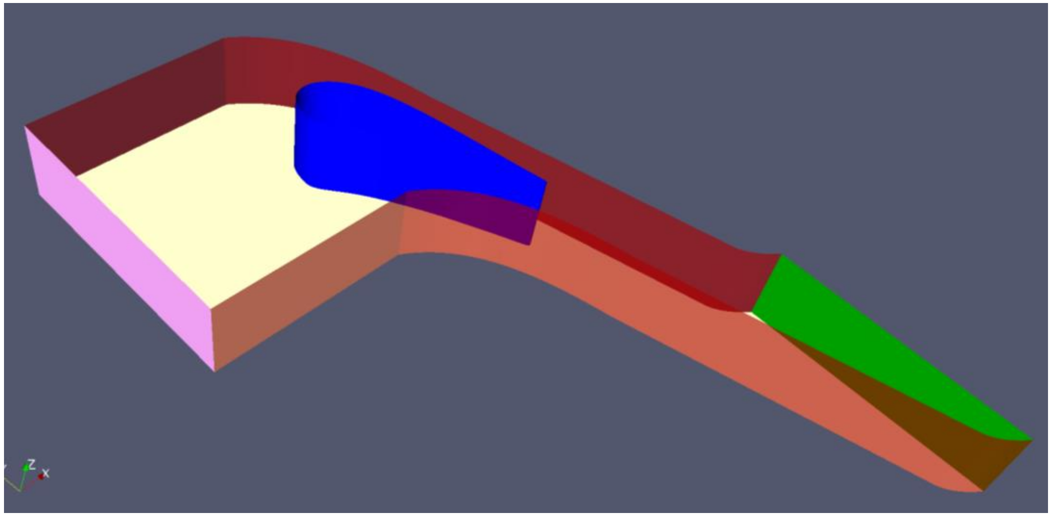
Boundary conditions

Patch name	Patch type
inlet	patch
mid	symmetryPlane
outlet	patch
tip	wall
vane	wall
periodic*	cyclic



Patch name	U	p
inlet	timeVaryingMappedFixedValue	zeroGradient
outlet	zeroGradient	fixedValue

Numerical setup

- Solver: steady state **simpleFoam**
- Discretization schemes: **2nd order**
- Advection term: **blended scheme (1st/2nd order)**
- Residual control: ending criterion of 10^{-9}
- Monitoring: 14 pressure and velocity probes
- **Two-equation turbulence models** with WallFunctions approach

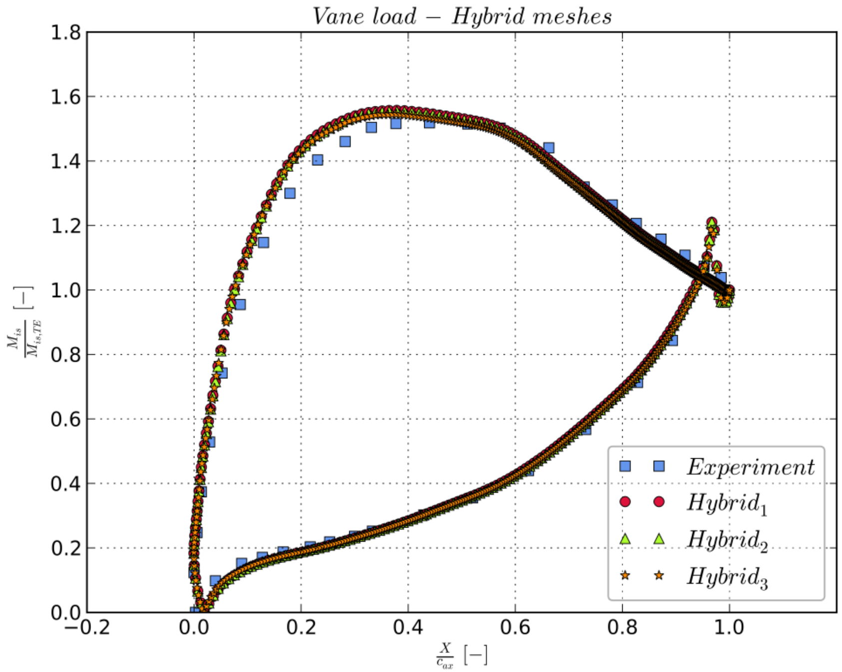
Mesh name	Turbulence model
$hybrid_1$	k-ε
$hybrid_2$	k-ε
$hybrid_3$	**k-ε/realisable k-ε/SST k-ω**

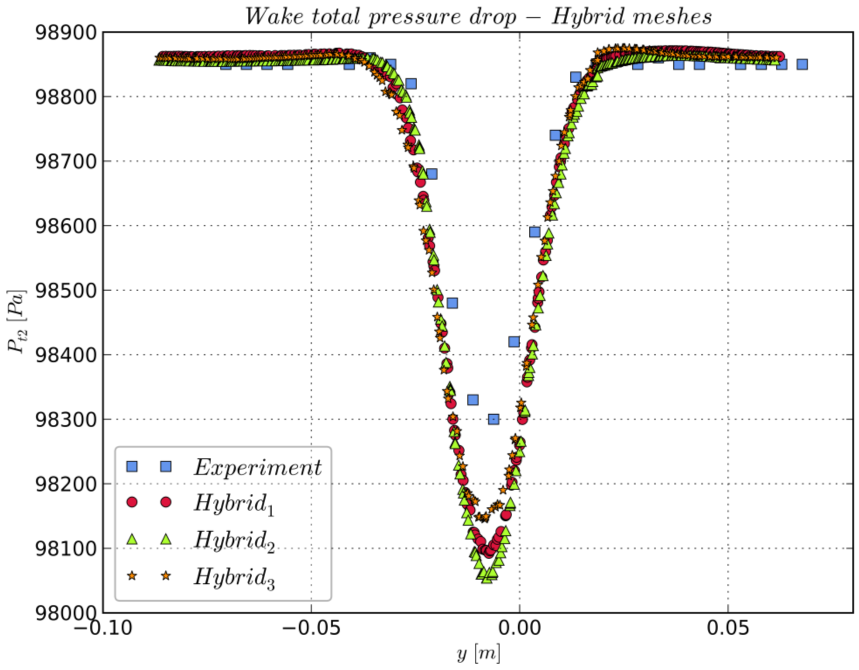
Results – Overview

Results will include the following:

- **Mesh sensitivity analysis** based on midspan flow features
  ↳Turbulence model: k-ε
- Evaluation of the **turbulence model** influence on the predictions of:
  - ✓ vane load
  - ✓ wake loss
  - ✓ secondary flows
- **Scalability** analysis over different HW configurations

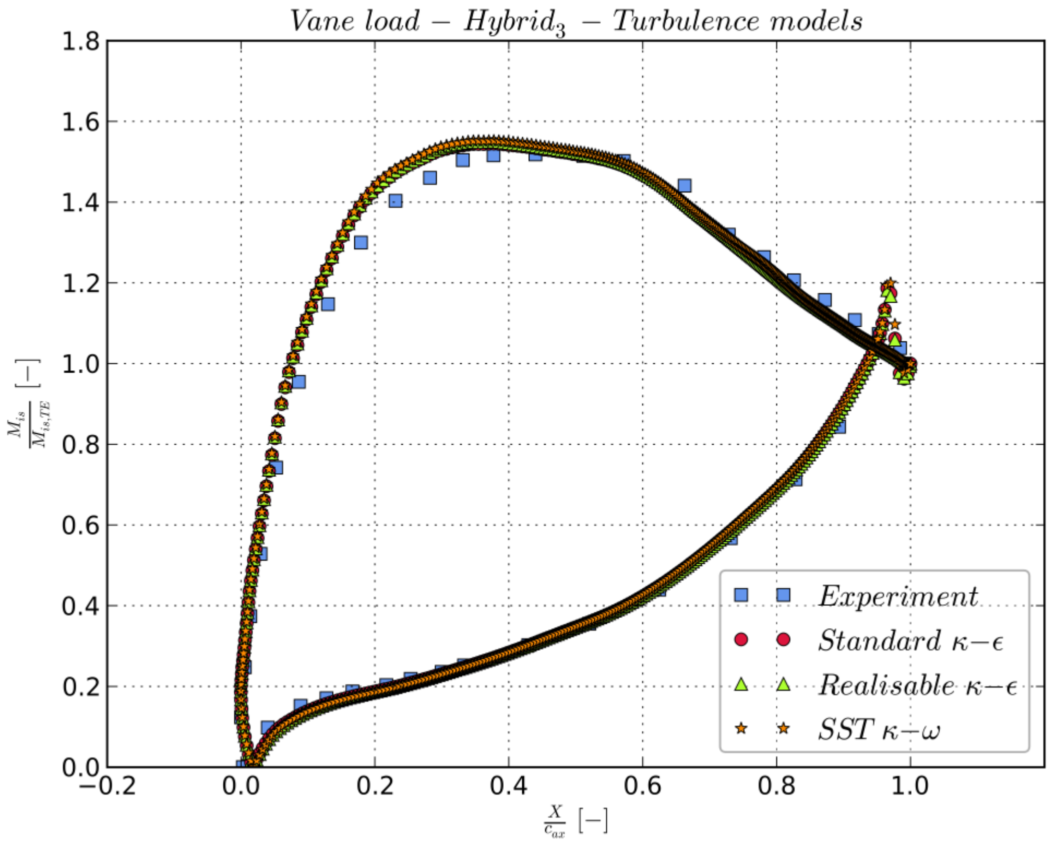
Results – Mesh sensitivity





Best mesh ➡ **$Hybrid_3$**

Results – Vane load



Vane load predictions have a weak dependence on turbulence model

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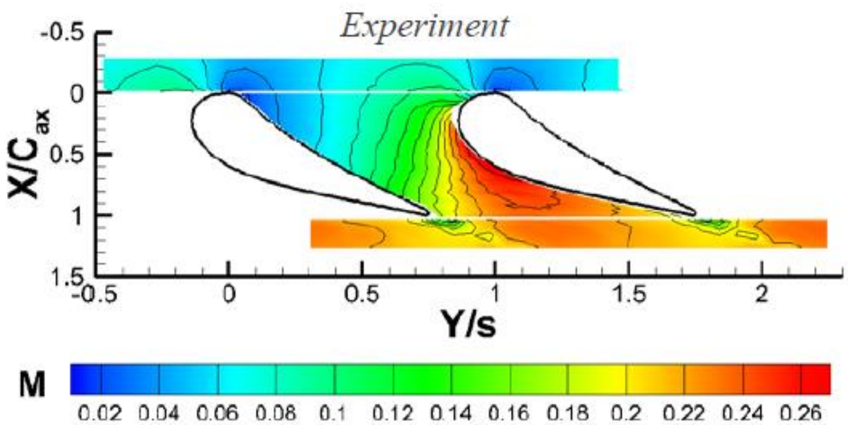
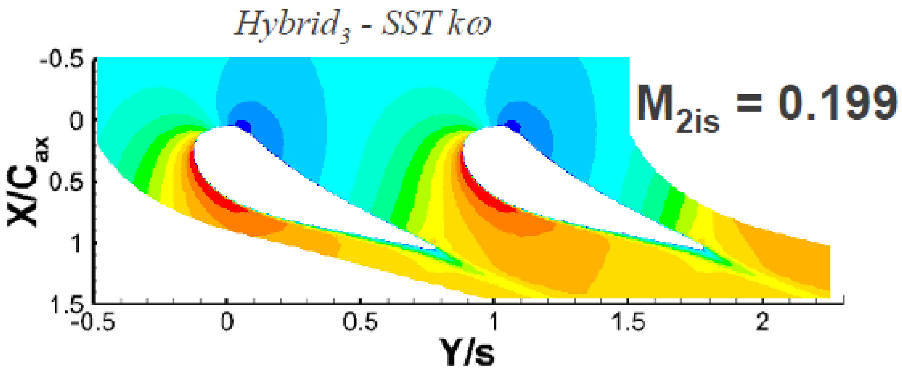
Results – Midspan velocity

(x/C_{ax}= 1.50)





Turbulence model marginally affects midpan velocity

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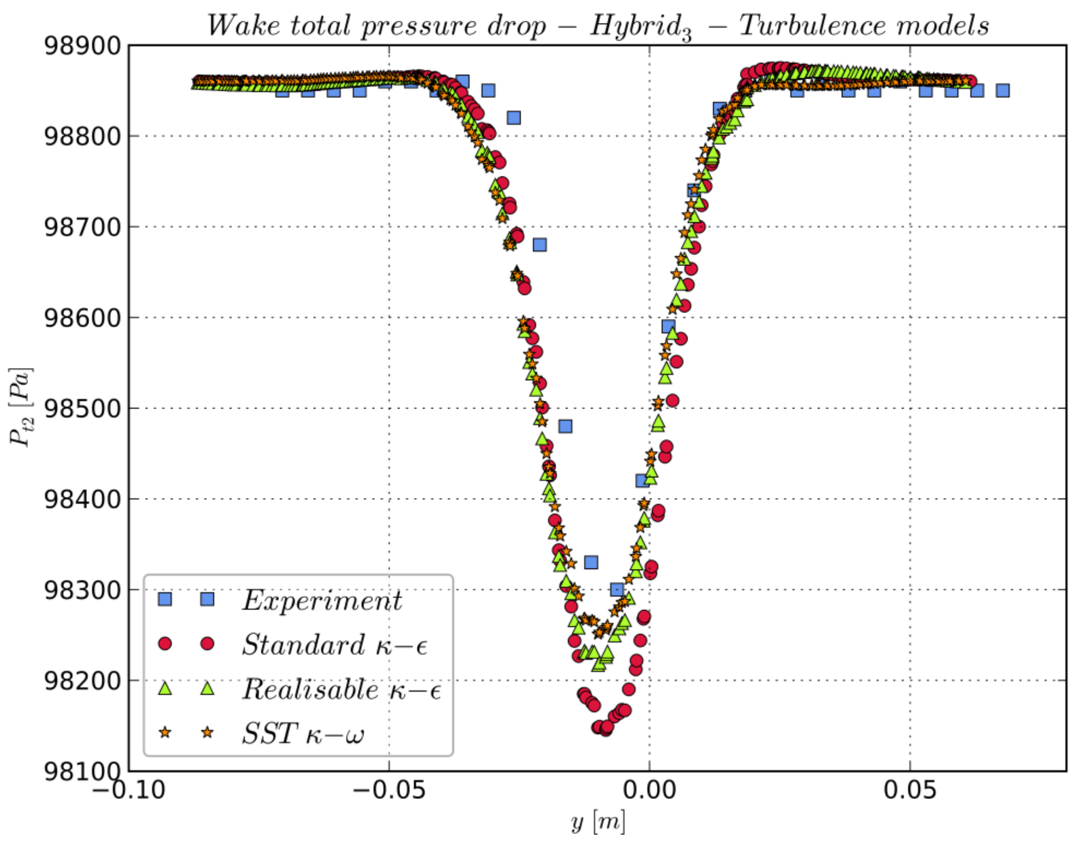
Results – Midspan wake

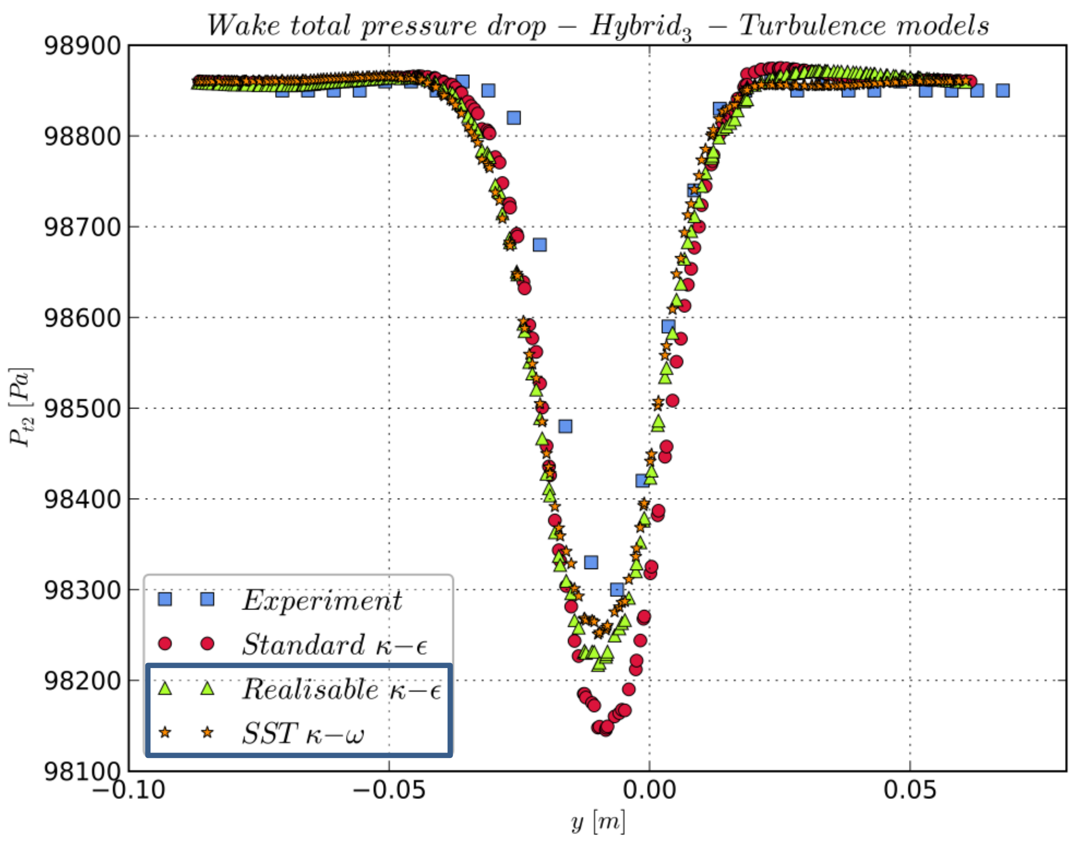
(x/C_{ax}= 1.50)



Wake predictions have a strong dependence on turbulence model

Results – Midspan wake

(x/C_{ax}= 1.50)



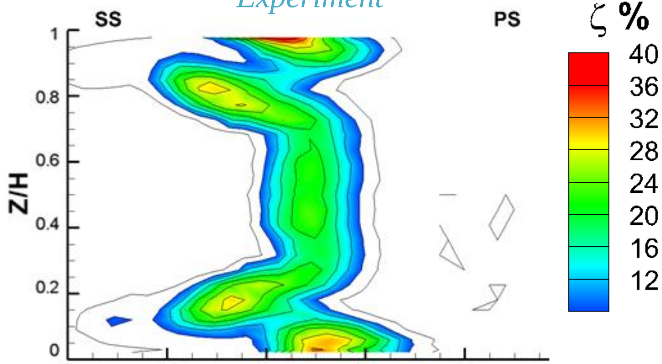
Wake predictions have a strong dependence on turbulence model

Results – Secondary flows

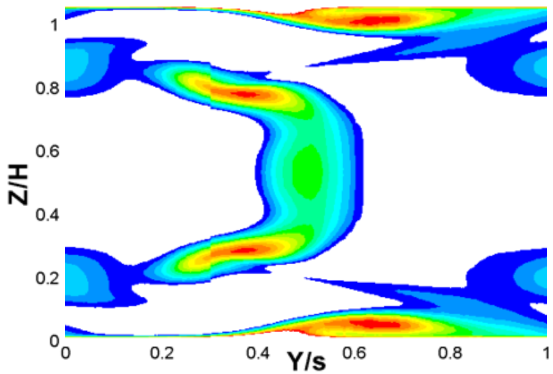
(x/C_{ax}= 1.53)

$$\zeta = \left(1 - \frac{U_2^2}{U_{2is}^2}\right) * 100$$

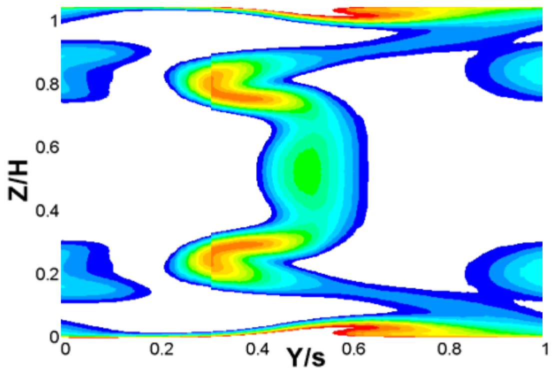
Experiment



Hybrid$_3$ - Realisable k-ε



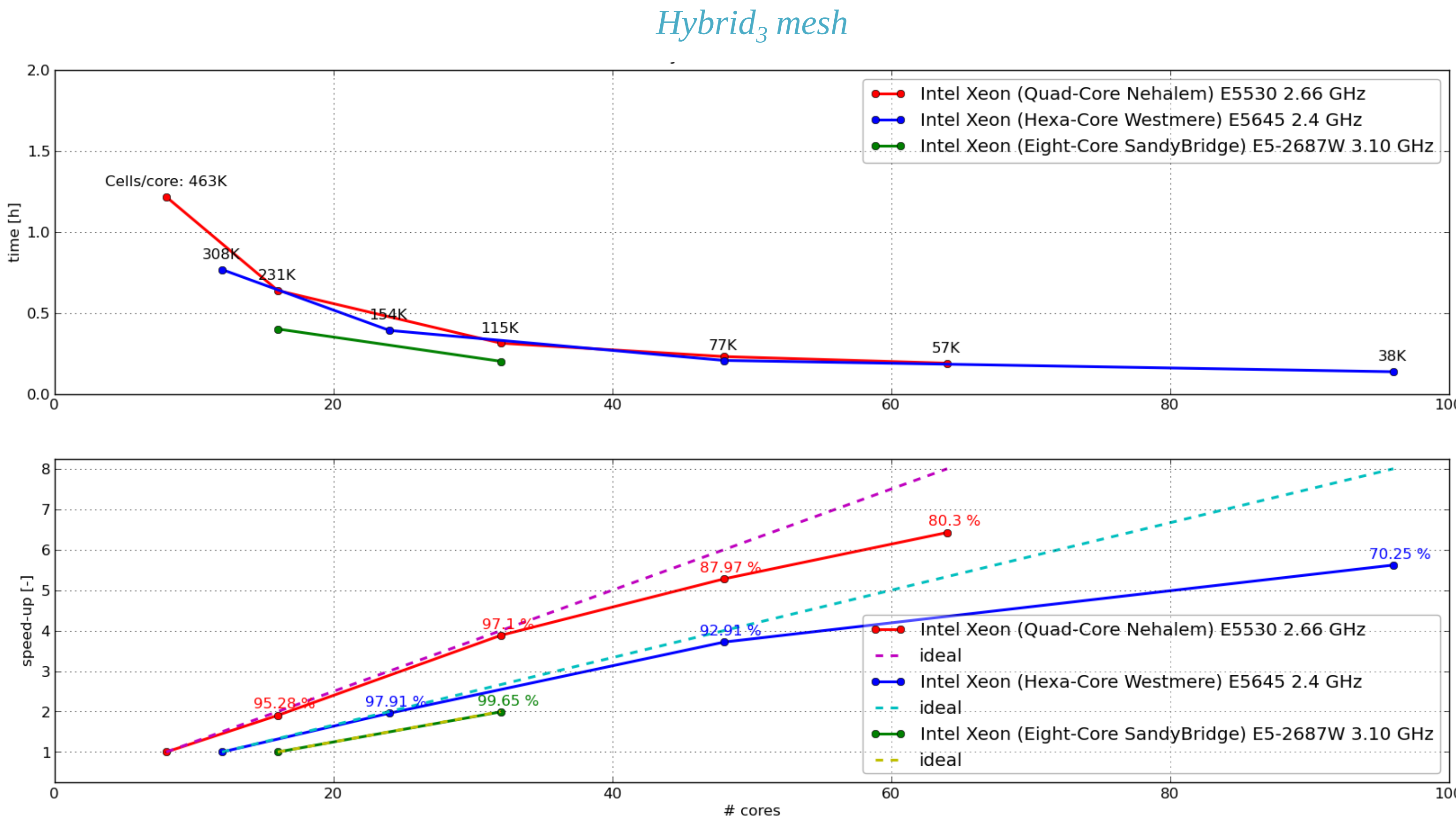
Hybrid$_3$ - SST k-ω



Scalability

Nehalem and **Westmere** cores are interconnected with **Infiniband DDR**

Sandybridge cores are interconnected with **Infiniband QDR**



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Conclusions

- ***Turbulence model***
  - ✓ The vane load prediction is satisfactory, especially on the pressure side.
  - ✓ *Realisable k-ε* and ***SST k-ω*** are the closest to the measured wake loss, with an overestimation of 15% and **9%**, respectively.
  - ✓ Simulations overpredicted the kinetic energy losses associated with the passage vortex and the corner vortex as well.

- ***Computational efficiency***
  - ✓ The scalability of the study-case is effective on the tested cores range thanks to the **HPC platform (HW+Interconnection)**.
  - ✓ Setup shows a good efficiency **(>80%)** using up to **38k cells per computational core**. This cell density per computational core can be used as reference for the same setup on larger problems.

Future developments

- Pre-processing: Mesh topology based on native openFoam pre-processor
- Compressibility to match experiments at $M_{2is} = 0.4 – 0.6$
- Thermal modelling to simulate film cooling applications
- Unsteadyness for an accurate prediction of the thermal mixing between mainstream and coolant flow

Questions?

Thank you for your kind attention!