CS2 - Spanwise periodic DNS/LES of transitional turbine cascades

5th International Workshop on High-Order CFD Methods

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Doc. ref.: N/A

Case Overview

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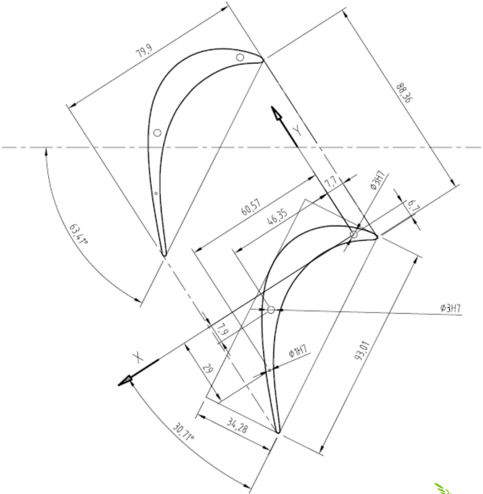
T106C (high lift)

- $Re_{2s} = 80.000$
- $M_{2s} = 0.65$
- Pitch/Chord = 0.95
- Span/Chord = 10%
- $\beta_1 = 32.7°$

T106A (nominal lift)

- $Re_{2s} = 60.000$
- $M_{2s} = 0.4$
- Pitch/Chord = 0.798
- Span/Chord = 10%
- $\beta_1 = 45.5°$
  (blockage correction)

Spanwise periodic computations



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- Air near vacuum $P^t \simeq 10.000\ Pa$ and ambient temperature $T^t \simeq T_{amb} \simeq 290K$
- Controlled conditions near the cascade
  - Inlet: total conditions T_1^t, P_1^t and flow angle β_1
  - Outlet: static pressure p_2
- Isentropic outlet Mach number M_{2s}

$$M_{2s}=\sqrt{\frac{2}{\gamma-1}\left(\left(\frac{P_1^t}{p_2}\right)^{-\frac{\gamma}{\gamma-1}}-1\right)}$$

- Isentropic outlet Reynolds number Re_{2s}

$$Re_{2s}=\frac{\rho_{2s}v_{2s}C}{\mu_{2s}}$$

with

$$f_{2s}=\left(1+\frac{\gamma-1}{2}M_{2s}^2\right) \quad T_{2s}=T_1^t\cdot f_{2s}^{-1} \quad \rho_{2s}=\frac{P_1^t}{\mathcal{R}T_1^t}\cdot f_{2s}^{-\frac{1}{\gamma-1}}$$

$$v_{2s}=M_{2s}\sqrt{\gamma\mathcal{R}T_{2s}} \quad \mu_{2s}=\mu_0\left(\frac{T_0}{T_{2s}}\right)^{3/2}\frac{T_0+S}{T_{2s}+S}$$

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- Boundary conditions
  - Inlet: total conditions $P_1^t = T_1^t = 1$ and flow angle β_1
  - Outlet: static pressure p_2

$$p_2 = f_{2s}^{-\frac{\gamma}{\gamma-1}}$$

- Gas properties
  - thermodynamic

$$\mathcal{R} = 1 \qquad \mathcal{C}_p = \frac{\gamma}{\gamma - 1} \qquad \gamma = 1.4$$

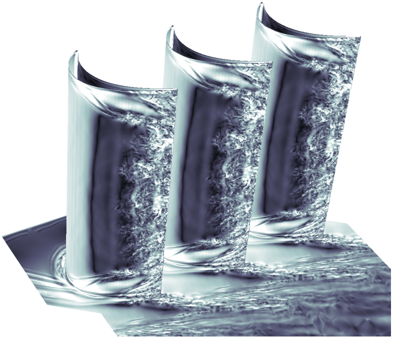
  - constant transport properties

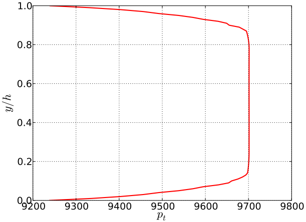
$$\mu = \frac{\rho_{2s} v_{2s} C}{Re_{2s}} \qquad \kappa = \frac{\mu \mathcal{C}_p}{\kappa}$$

using isentropic state

$$v_{2s} = M_{2s} \sqrt{\gamma \cdot f_{2s}^{-1}} \qquad \rho_{2s} = f_{2s}^{-\frac{1}{\gamma-1}}$$

Case Overview
Description: 2D flow ?





Low Reynolds effects

- thick inlet boundary layers
- important secondary flow/horseshoe
- interaction with laminar separation bubble
- full 3D flow, non-constant blockage
- angle correction sometimes successful . . .
- . . . but apparently not in this case

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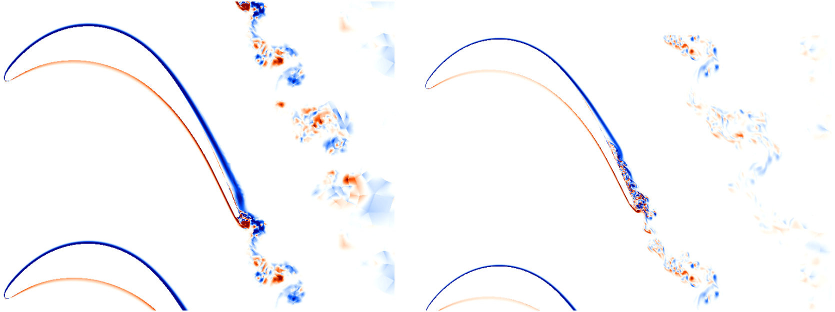
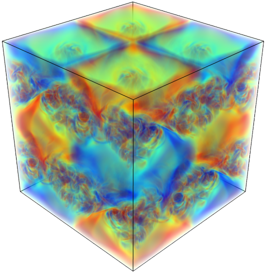


T106A, Re=60.000 | T106C, Re=80.000

Case Overview
Validation cases: DNS & LES capabilities

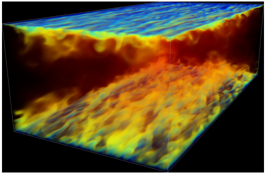
WS1 - transition of the Taylor-Green vortex $Re = 1600$

- DNS / LES of transitional flow
- validation DNS/LES/ILES
- kinetic energy budget
- role/importance of numerical dissipation
- resolution requirements Δ, Δt
- stability



WS2 - channel flow $Re_\tau = 550$

- resolved LES of wall boundary layer
- validation of LES/ILES
- momentum budgets viscous / Reynolds stresses
- resolution requirements Δx^+, Δy^+, Δz^+ and Δt^+, as well as stretching



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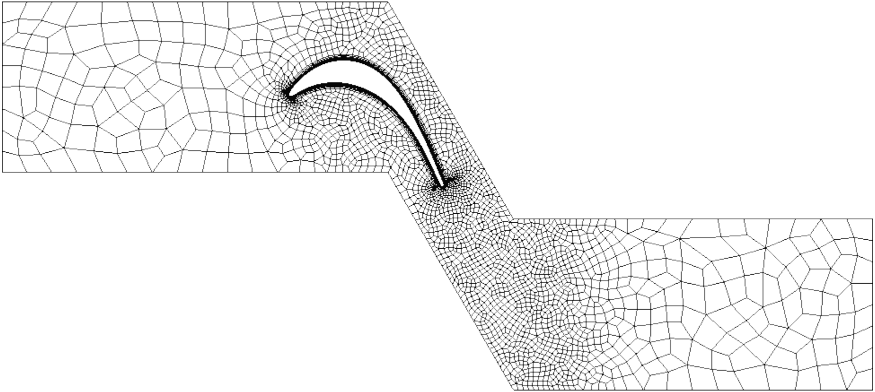
Case Overview
Workshop meshes: coarse (21k Elements)



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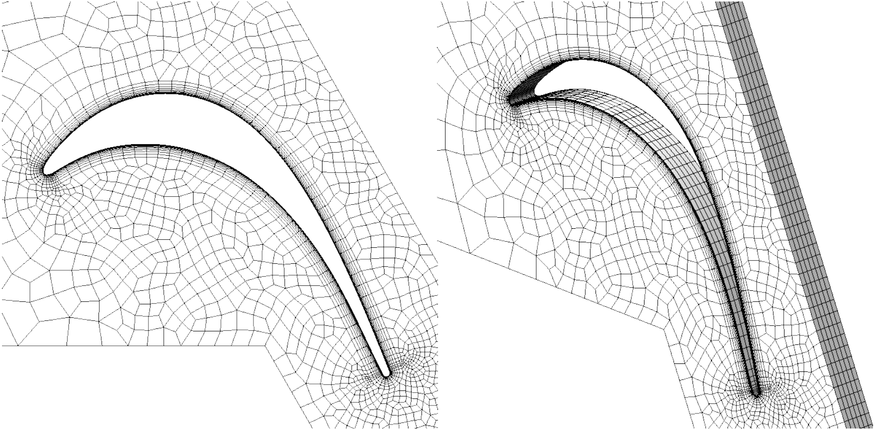

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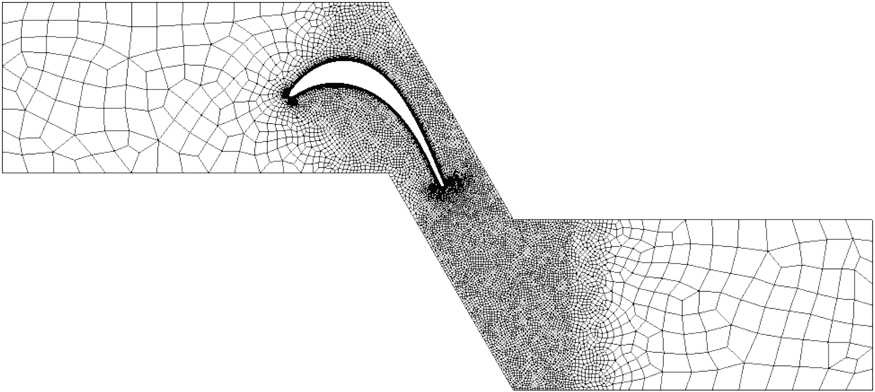
Workshop meshes: baseline (118k Elements)



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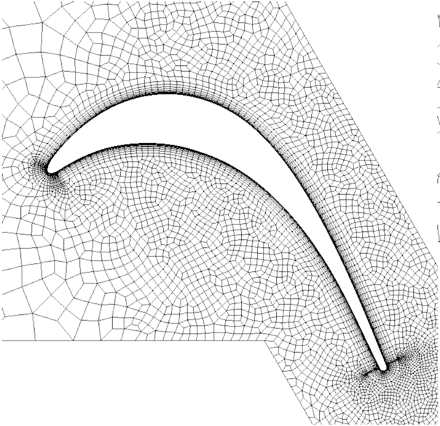
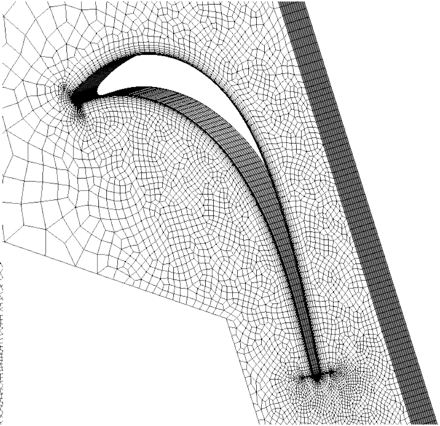
Workshop meshes: baseline (118k Elements)





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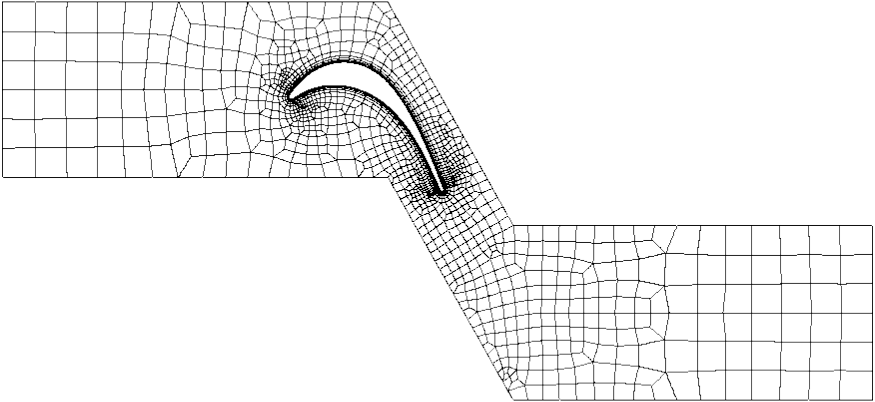
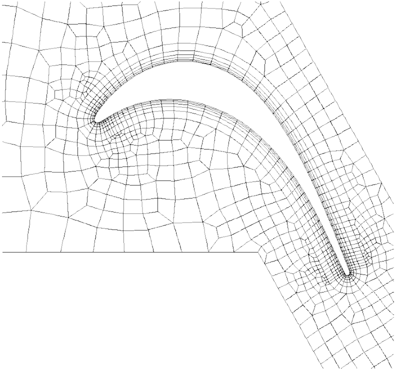
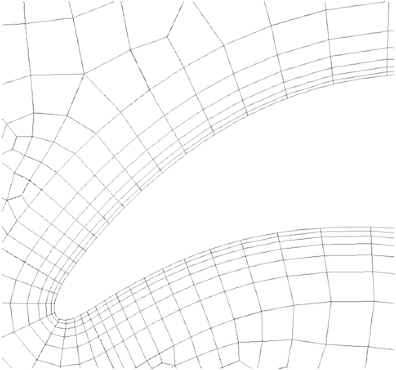
Case Overview
IAG Stuttgart meshes(4359 Elements)



Case Overview
IAG Stuttgart meshes(4359 Elements)





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Results Comparison

Results Comparison
Computations

	Method	Resolution	DOF	Avg. CT	Ite/CT
Onera	LLF/SIP Pascal basis	P4 coarse	1.1M	30	64479
		P5 coarse	1.7M	30	135406
		P3 baseline	2.9M	30	27633
		P4 baseline	5.1M	30	56419
		P5 baseline	8.2M	30	123096
IAG	Roe/BR1 Tensor basis	P6 coarse	1.5M	40	4838
		P7 coarse	2.7M	40	5908
MIT[1]	IEDG [2]	P2 baseline	3.2M[3]	7.7	270
Cenaero	Roe/SIP Tensor basis	P4 coarse	2.6M	20	451
		P4 baseline	14.8M	18	902

[1] Corrected post-processing
[2] Interior Embedded DG
[3] Before static condensation

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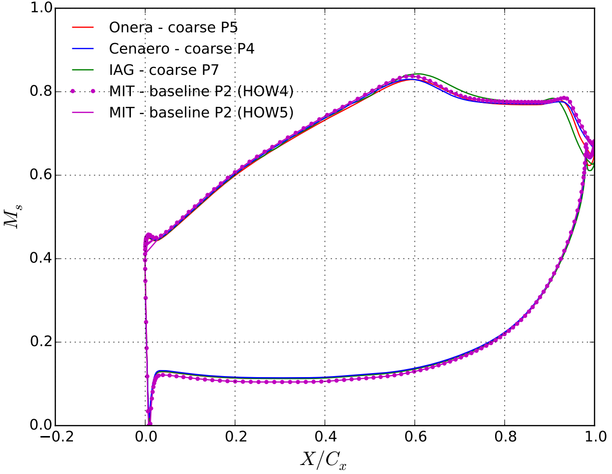
Results Comparison

Blade distributions: isentropic Mach number



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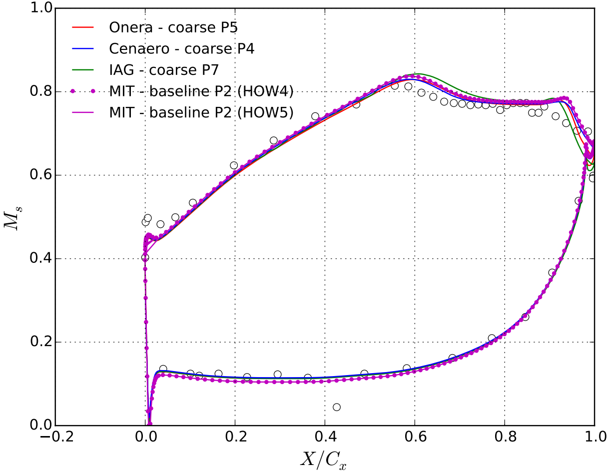
Results Comparison

Blade distributions: isentropic Mach number



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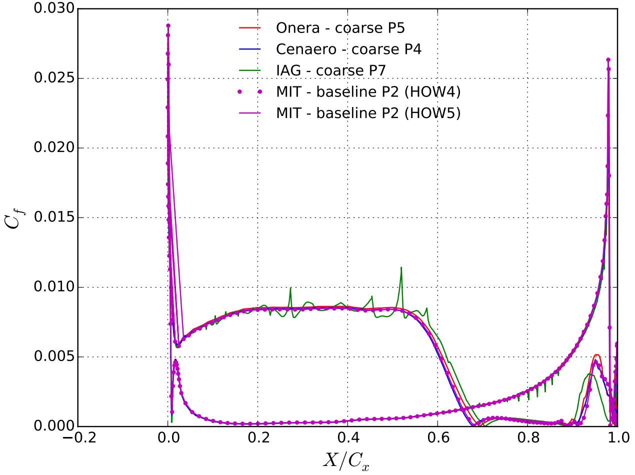
Results Comparison
Blade distributions: friction coefficient



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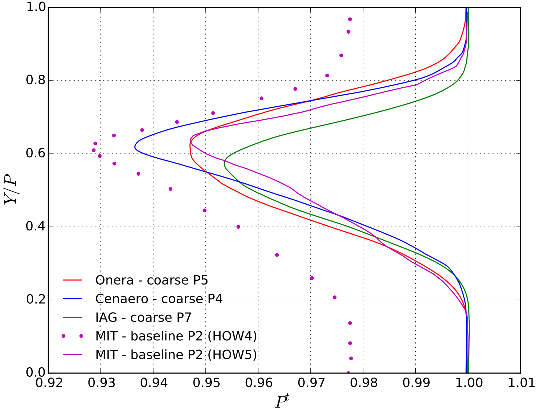
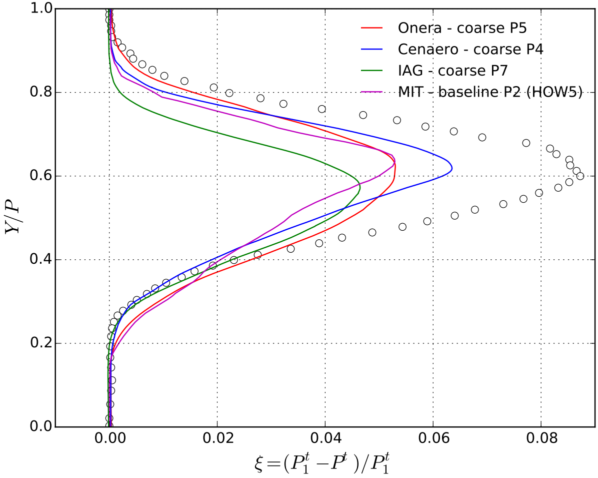
Results Comparison
Wake traverses: total pressure



Note: previous MIT results featured post-processing error, now corrected (HOW4 vs HOW5)

Results Comparison

Wake traverses: loss coefficient



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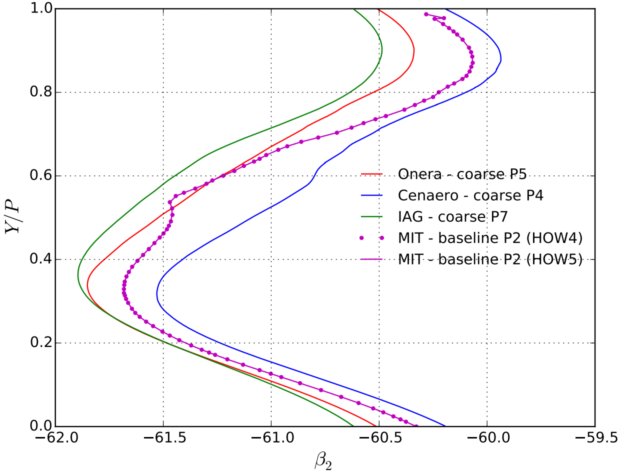
Results Comparison
Wake traverses: flow angle



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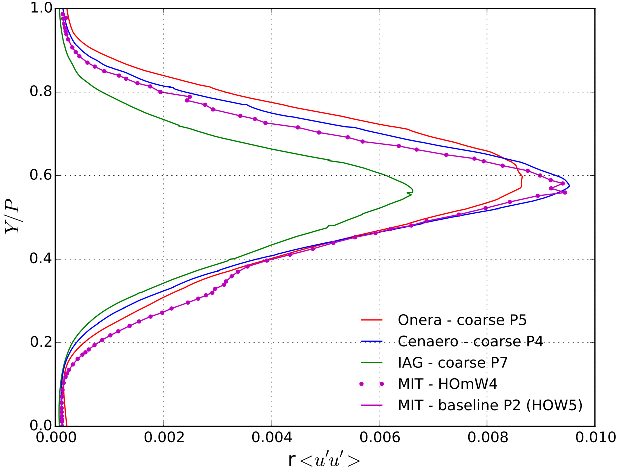
Results Comparison

Wake traverses: Reynolds stress component $< u'u' >$



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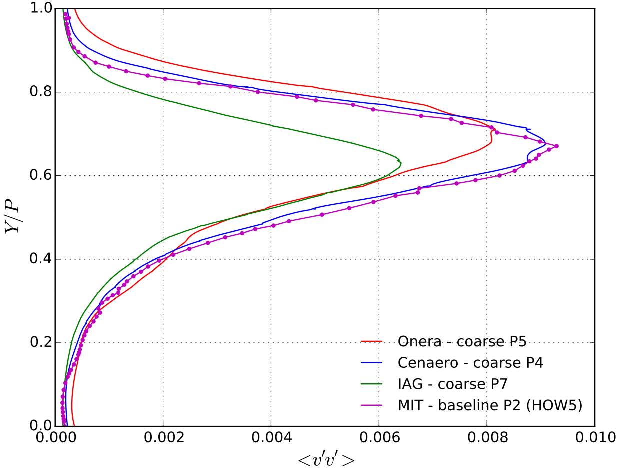
Results Comparison

Wake traverses: Reynolds stress component $< v'v' >$



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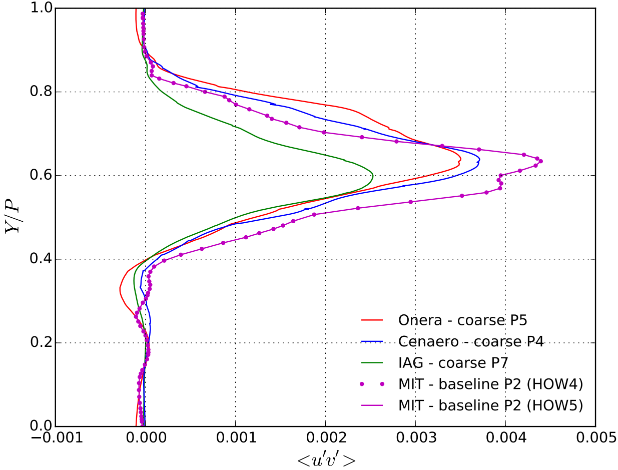
Results Comparison

Wake traverses: Reynolds stress component $< u'v' >$



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Results Comparison
Computational resources

	Method	Resolution	DOF	Ite/CT	WU/CT	WU/DOF/CT
Onera	LLF/SIP Pascal basis	P4 coarse	1.1M	64479	0.31M	0.292
		P5 coarse	1.7M	135406	1.23M	0.716
		P3 baseline	2.9M	27633	0.45M	0.141
		P4 baseline	5.1M	56419	1.70M	0.332
		P5 baseline	8.2M	123096	4.64M	0.566
IAG	Roe/BR1 Tensor basis	P6 coarse	1.5M	4838	0.10M	0.069
		P7 coarse	2.7M	5908	0.15M	0.068
MIT	IEDG	P2 baseline	3.2M	270	0.04M	0.013
Cenaero	Roe/SIP Tensor basis	P4 coarse	2.6M	451	0.29M	0.110
		P4 baseline	14.8M	902	4.38M	0.295

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Results Comparison
Computational resources

	Method	Resolution	DOF	Ite/CT	WU/CT	WU/DOF/RES
Onera	LLF/SIP Pascal basis	P4 coarse	1.1M	64479	0.31M	$1.13\mu\ s$
		P5 coarse	1.7M	135406	1.23M	$1.32\mu\ s$
		P3 baseline	2.9M	27633	0.45M	$1.27\mu\ s$
		P4 baseline	5.1M	56419	1.70M	$1.47\mu\ s$
		P5 baseline	8.2M	123096	4.64M	$1.15\mu\ s$
IAG	Roe/BR1 Tensor basis	P6 coarse	1.5M	4838	0.10M	$2.87\mu\ s$
		P7 coarse	2.7M	5908	0.15M	$2.31\mu\ s$
MIT	IEDG	P2 baseline	3.2M	270	0.04M	$0.17\mu\ s$
Cenaero	Roe/SIP Tensor basis	P4 coarse	2.6M	451	0.29M	$2.68\mu\ s$
		P4 baseline	14.8M	902	4.38M	$3.63\mu\ s$

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Conclusions

Results

- Onera/Cenaero/MIT: close results
  - post-processing error MIT resolved
  - Similar numerical implementations
  - Used the same meshes!!
- IAG: error in mesh setup
  - Mesh has to be redone (smoothness of normals)
  - Wake refinement probably needed
  - Workshop-provided grids would likely close the gap

Timings

- Comparison are difficult
- Onera/Cenaero: comparable (despite EXP/IMP)
- IAG: Faster but not more efficient (large time-step)
- MIT: IEDG seems promising (DOF count? Dealiasing?)

Evolution of the test case

- true grid convergence studies and free mesh choice ?
- adaptative computations ?
- 3D full span computations ?

All options are costly ...

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Experimental match

- Confirmed disagreement identified during HOW2
- Large scale three-dimensionality detected by 3D LES
- angle correction - often used in literature - does not help
- bad match probable reason for which very few LES / DNS in literature
- Data seems not suitable for RANS/transition model development for 2D transition modes → **pure numerical** data (DNS)
  - full specification possible, whereas not all can be measured
  - much more detailed data available
  - truely 2D conditions can be reproduced
- Data should be used for reference of 3D computations → more detailed data are required
  - inlet boundary layer
  - characterization of 3D effects (spanwise traverses, ...)

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