HELICOPTER HOVER CFD SIMULATIONS:

**An Investigation of
Various Far-Field Boundary and Initial Conditions via DLR’s
Legacy Block-Structured FLOWer CFD Solver**

DLR

Alexios N Philippou, Institute of Aerodynamics and Flow Technology,13/02/2023

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DLR

Research Motivation

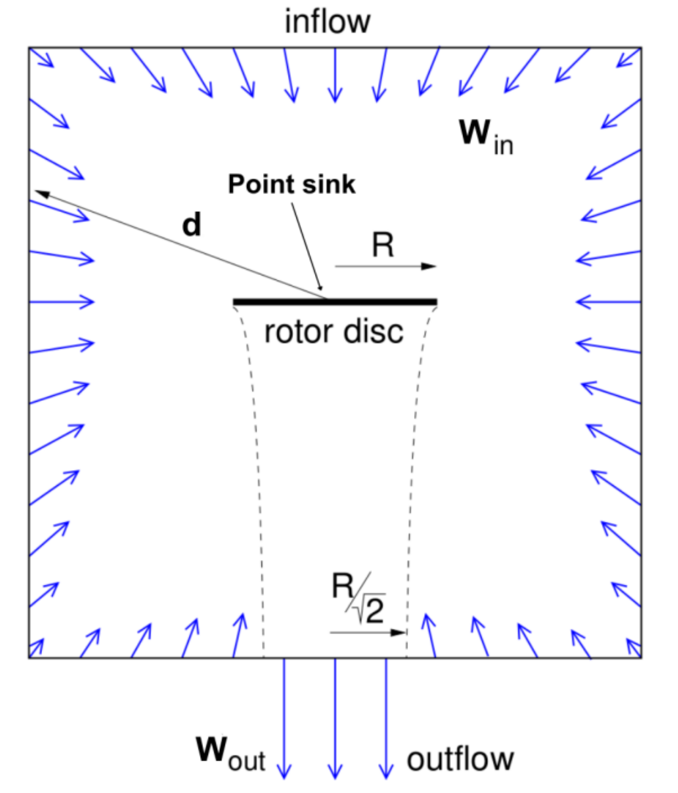
- Stationary hover is one of the most crucial flight conditions for a helicopter.
- Reaching steady state from freestream (Quiescent flow) can take considerable time.
- Bringing far-field closer to source of disturbance can decrease computational cost.
- Initializing flow field can aid in expediting solution (supposedly).

Existing Boundary Conditions

Standard far-field condition

- Focuses on creating a theoretically unbounded domain.
- Specifying free stream conditions such as density, velocity, and pressure, for the boundary
- Must be allocated far enough from the source of disturbance, in a region where the flow is meant to resemble free stream conditions.

Froude Source-Sink far-field condition [1]



- Based on actuator disk theory
- 1D momentum theory along axis of rotation
- Supposedly allows shorter finite far field distance

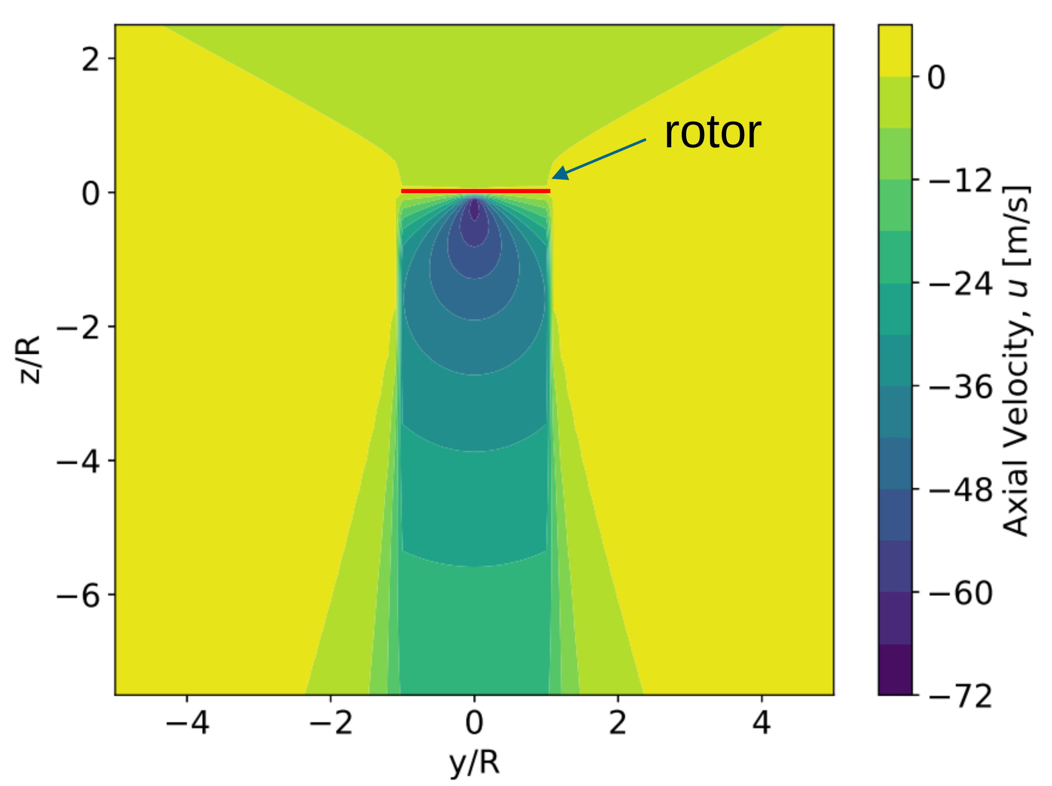
$$W_{in} = -\frac{V_{tip}}{4}\sqrt{\frac{C_T}{2}}\left(\frac{R}{d}\right)^2$$

$$W_{out} = -2V_{tip}\sqrt{\frac{C_T}{2}}$$

New/Contemporary Boundary Conditions

Jia’s Modified Version of the Spalart Model [2]

Axial Velocity



- Based on a static jet function
- Velocities decay with 1/r instead of $1/r^2$
- Inject an approximate representation of the wake underneath the actuator disk
- Supposedly allows shorter finite far field distance

New/Contemporary Boundary Conditions

Jia's Modified Version of the Spalart Model

Spherical Components

$$u_r = \frac{-A}{r_m}\sqrt{\frac{T}{\rho}}\left[f_m(\theta_m) + \tan\left(\frac{\theta_m}{2}\right)\frac{d\theta_m}{d\theta}\bigg|_{\theta_m}\right]$$

$$u_\theta = \frac{A}{r_m}\sqrt{\frac{T}{\rho}}\tan\left(\frac{\theta_m}{2}\right)f_m(\theta_m)$$

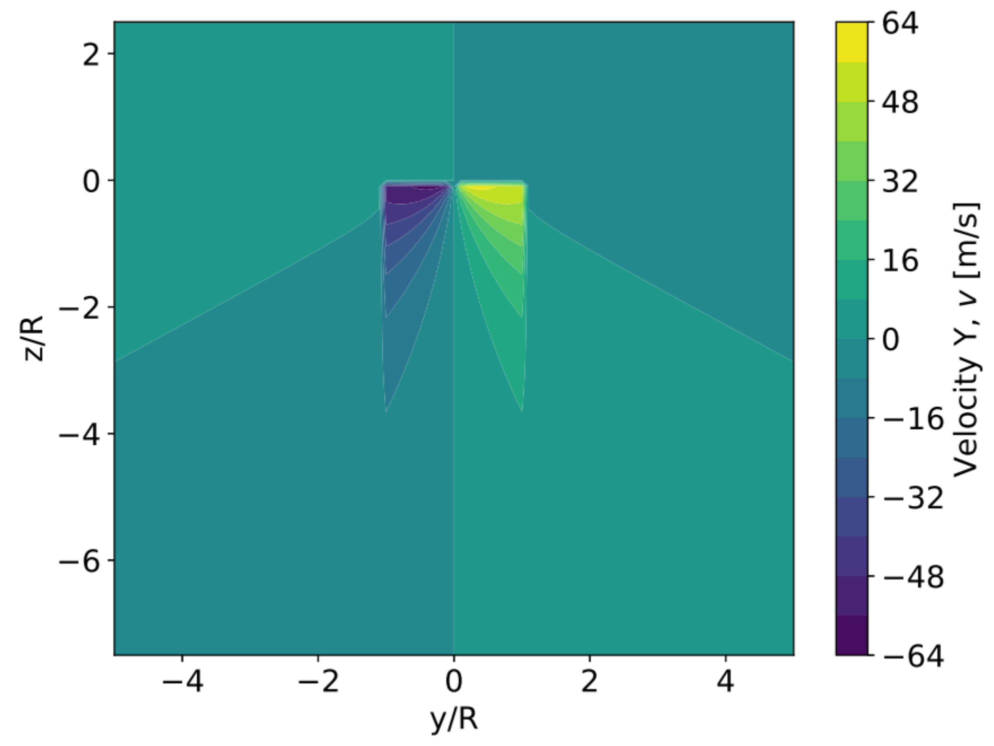
Jet Function

$$f_m(\theta) = 1 - exp\left(-\left[\frac{\cos\theta/2}{\sigma/2}\right]^2\right)$$

Induced Velocity of a Hovering Rotor

$$v_i = \sqrt{\frac{T}{2\rho A_r}}$$

Y Velocity



Parametric Studies

Test Type	Case	Grid used	Turbulence Model	Boundary Condition	Initial Condition	Convergence Tolerance
Convergence Criteria Investigation	1	M2 25R	SA	Froude	QuiscentFlow	1E-06
	2					1E-05
	3					1E-04
	4					1E-03
Turbulence Model Investigation	5	M2 6R	SA	Froude	QuiscentFlow	1E-06
	6		SA (0 Coef)			
	7		SST			
	8	M2 25R	SA	Froude	QuiscentFlow	1E-06
	9		SA (0 Coef)			
	10		SST			
	11	M1 25R	SA	Froude	QuiscentFlow	1E-06

Domain type:
M = Monocoque
C = Chimera

Grid Level:
1 = finest
2 = coarsest

Downstream Fairfield boundary location in blade radii

Parametric Studies

DLR

Test Type	Case	Grid used	Turbulence Model	Boundary Condition	Initial Condition	Convergence Tolerance
Convergence Criteria Investigation	1	M2 25R	SA	Froude	QuiscentFlow	1E-06
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	9		SA (0 Coef)			
	10		SST			
	11	M1 25R	SA	Froude	QuiscentFlow	1E-06

Reason:
- Stability
- Accuracy

Parametric Studies

Test Type	Case	Grid used	Turbulence Model	Boundary Condition	Initial Condition	Convergence Tolerance
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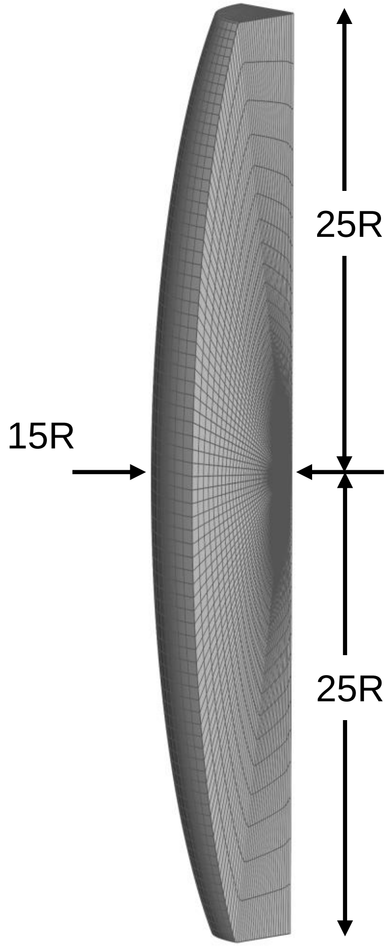
	9		SA (0 Coef)			
	10		SST			
	11	M1 25R	SA	Froude	QuiscentFlow	1E-06

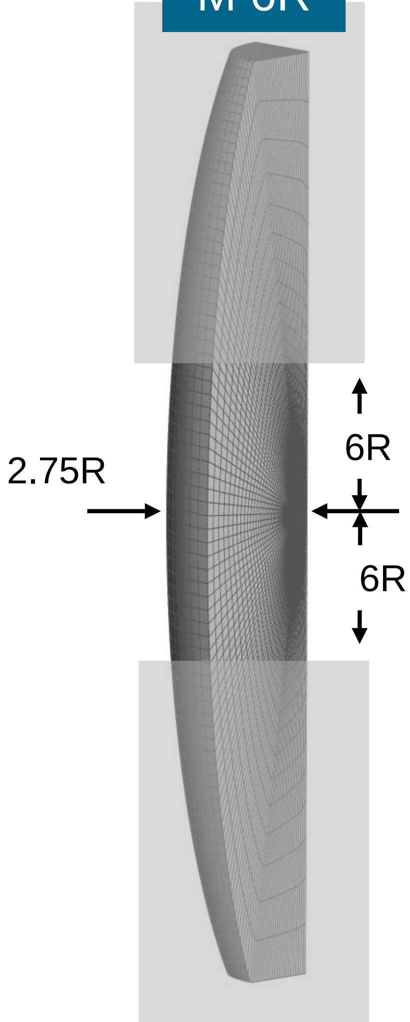
Reason:
- Less computationally demanding
- Better convergence
- 15% faster than Menter SST

Mesh and Settings

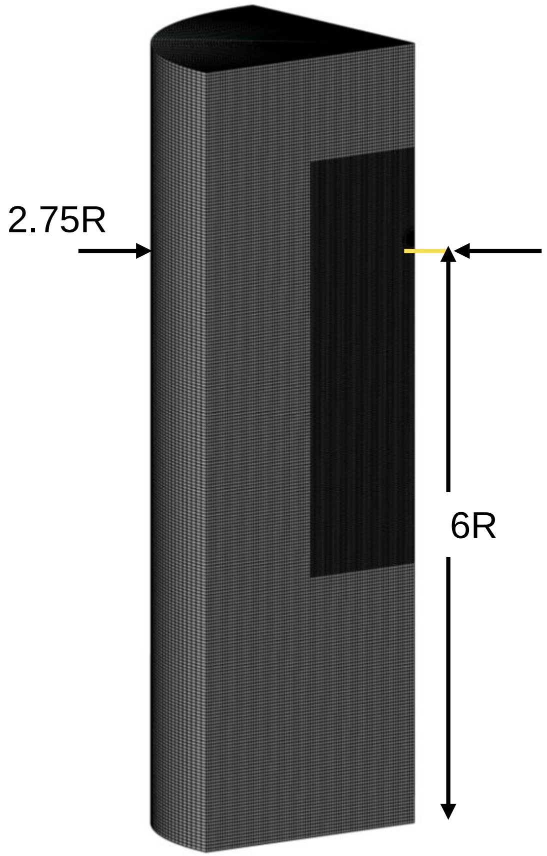
M 25R



M 6R



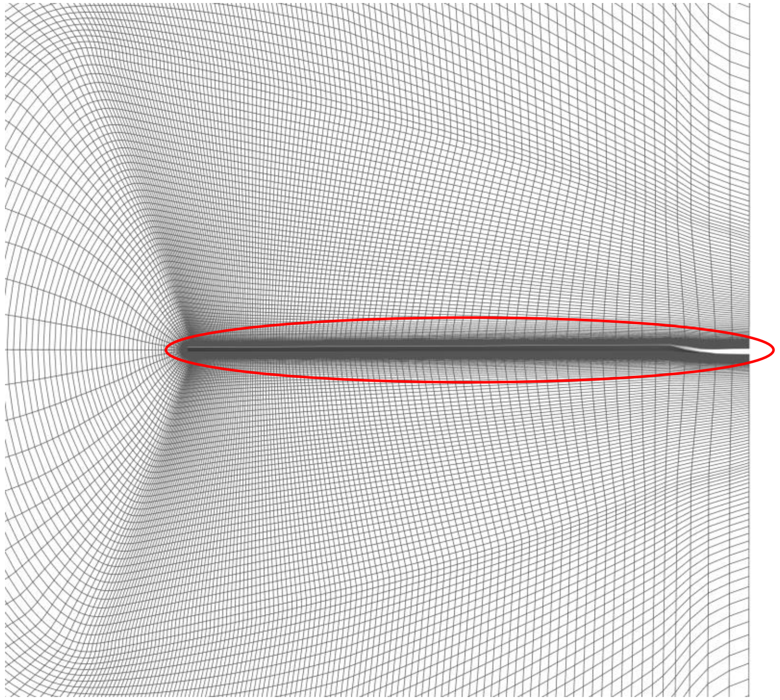
C 6R



Mesh and Settings

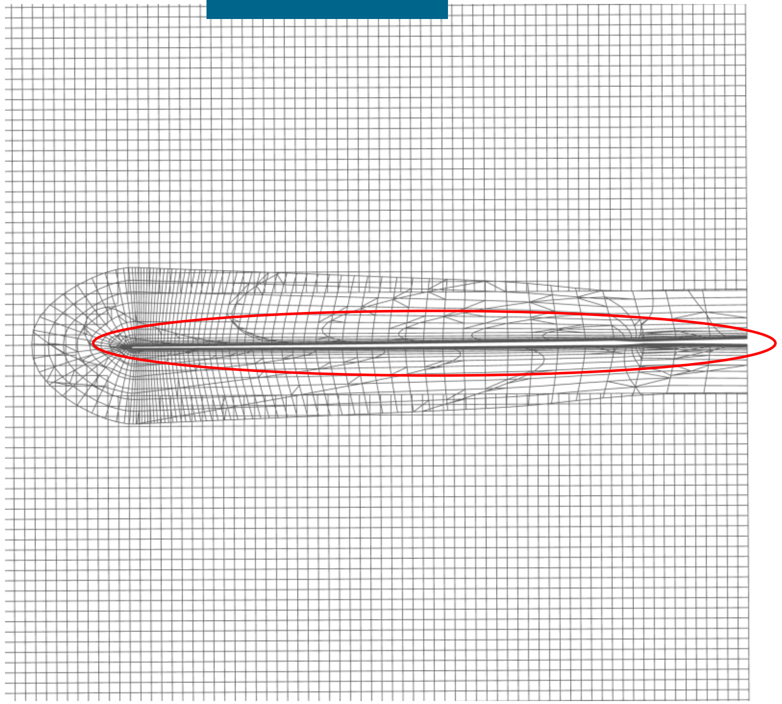
Blade back view

Monocoque



Blade

Chimera



Mesh and Settings

Fundamental Constant Settings	
Temporal Intergration scheme (main + turbulence equations)	Backward Euler LU-SGS [3]
Order of implicit dual time stepping scheme	2
Space discretization scheme for main equations	Finite Volume + Upwind Scheme
Finite Volume upwind scheme	SLAU2 with Albada limiter [4]
Order of spatial accuracy of upwind scheme	4
Cell discretization scheme	Cell-centered
Vortex Modification	Dacles-Mariani et al. [5]
Reference tip mach number	0.6423
Reference rotor radius (grid units)	2
Angle of Attack (deg)	9.5
Rotor Model	HART II [6]

Results and Conclusions

Test Type	Case	Grid used	Turbulence Model	Boundary Condition	Initial Condition	Convergence Tolerance
BC and IC condition Investigation	12	M2 25R	SA	Froude	QuiscentFlow	1E-06
	13			Standard	QuiscentFlow	
	14			New Model	New Model	
	15	M2 6R	SA	Froude	QuiscentFlow	1E-06
	16			Standard	QuiscentFlow	
	17			New Model	New Model	
	18	C2 6R	SA	Froude	QuiscentFlow	1E-06
	19			Standard	QuiscentFlow	
	20			New Model	New Model	
	21	C2 6R	SA	New Model	QuiscentFlow	1E-06
	22	C1 6R	SA	Froude	QuiscentFlow	1E-06
	23			Standard	QuiscentFlow	
	24			New Model	New Model	

Results and Conclusions

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	16			Standard	QuiscentFlow	
	17			New Model	New Model	
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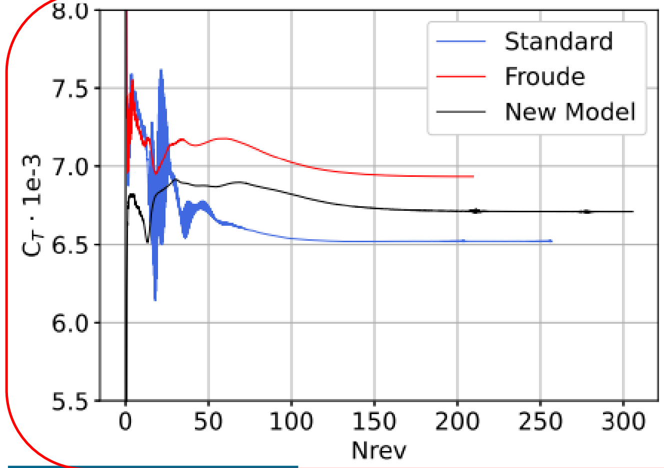
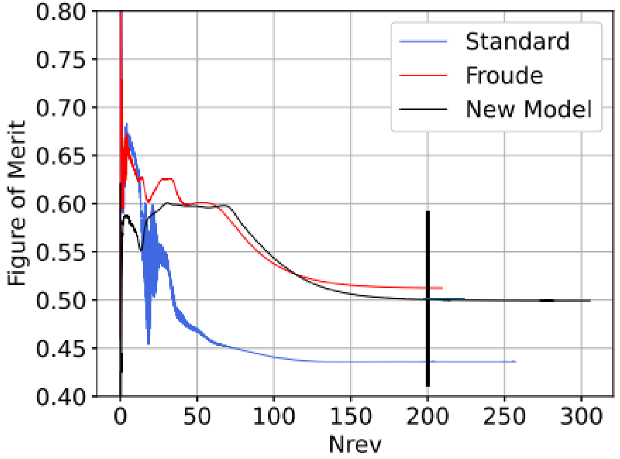
	19			Standard	QuiscentFlow	
	20			New Model	New Model	
	21	C2 6R	SA	New Model	QuiscentFlow	1E-06
	22	C1 6R	SA	Froude	QuiscentFlow	1E-06
	23			Standard	QuiscentFlow	
	24			New Model	New Model	

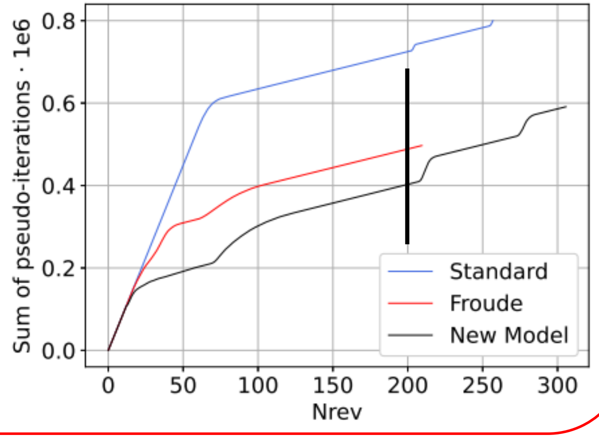
Monocoque domain tests (cases 12–17)

Plots of CT, FM, and pseudo-iteration sum for Monocoque Grids

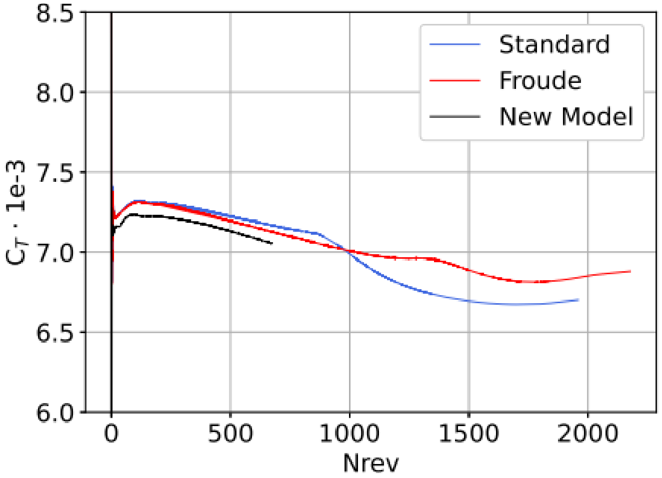
M2 6R

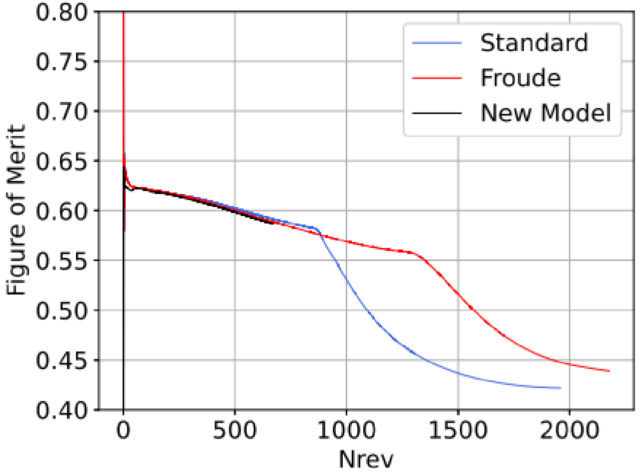


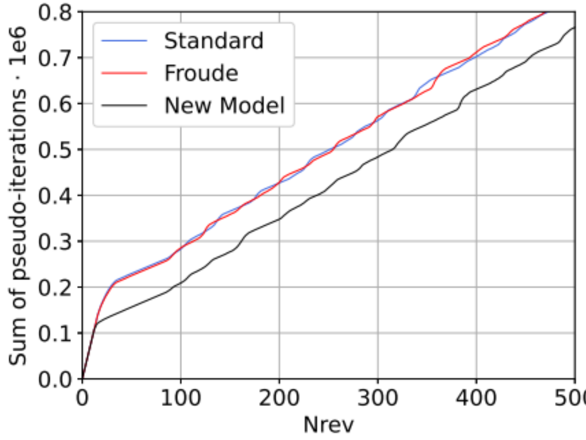




M2 25R

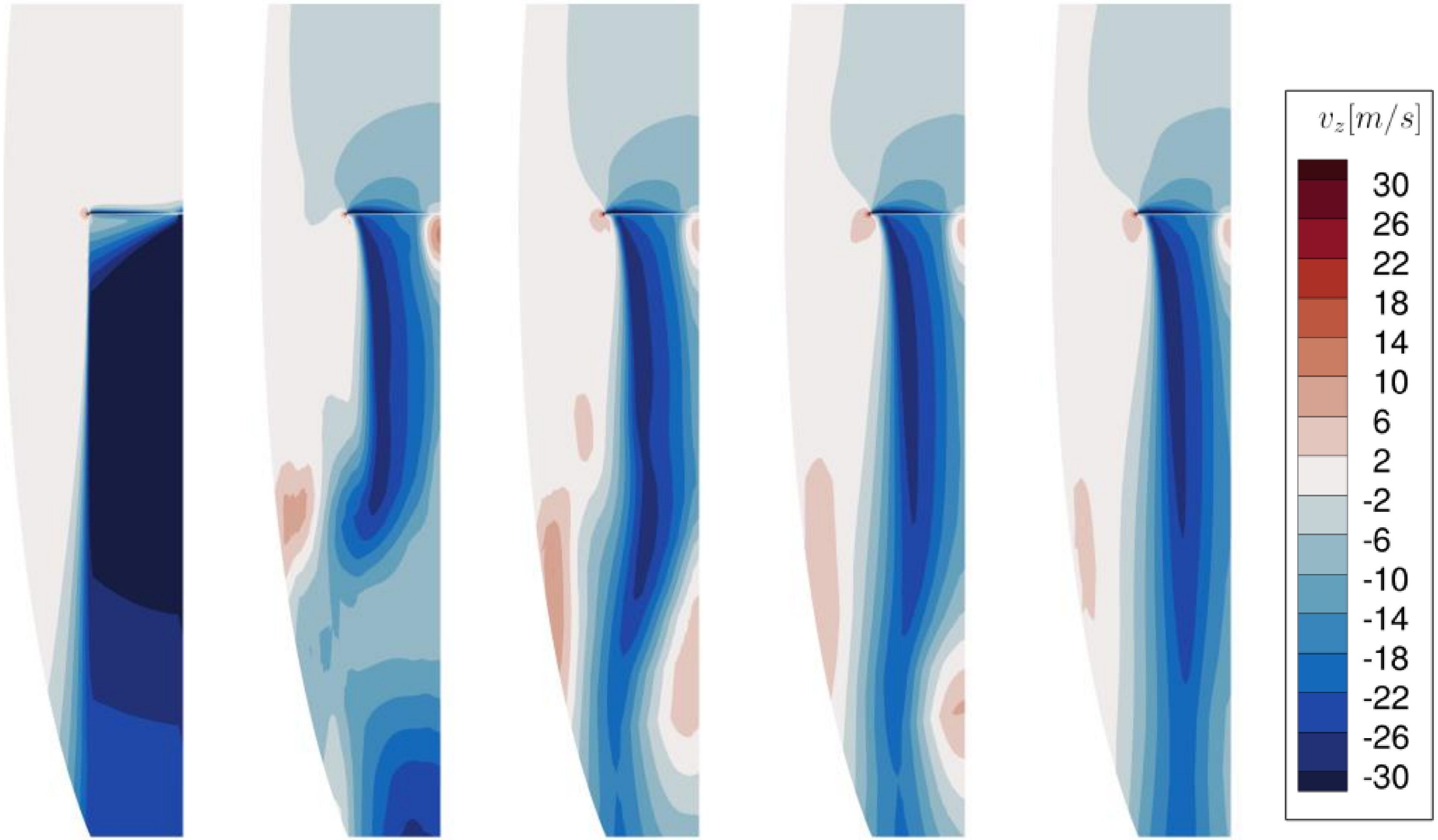






Axial Velocity Field Evolution Contour Plots

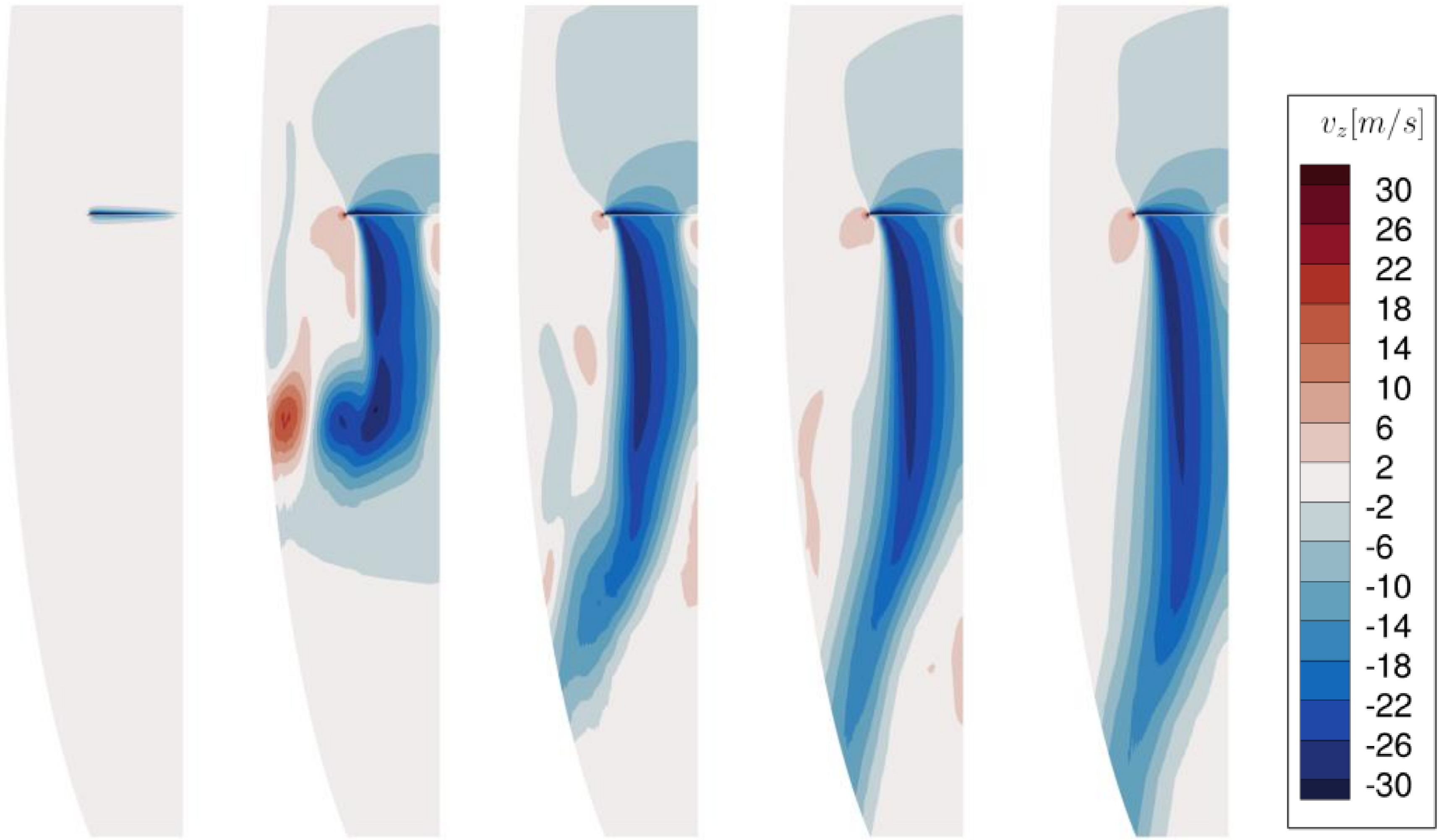
Test details:	
Grid	M2 6R
BC	New
IC	New
Framerate(rev)	10



Research Motivation | Existing Boundary Conditions | New Boundary Conditions | Parametric Studies | Mesh and settings | Results and Conclusions

Axial Velocity Field Evolution Contour Plots

Test details:	
Grid	M2 6R
BC	Froude
IC	QF
Framerate(rev)	10



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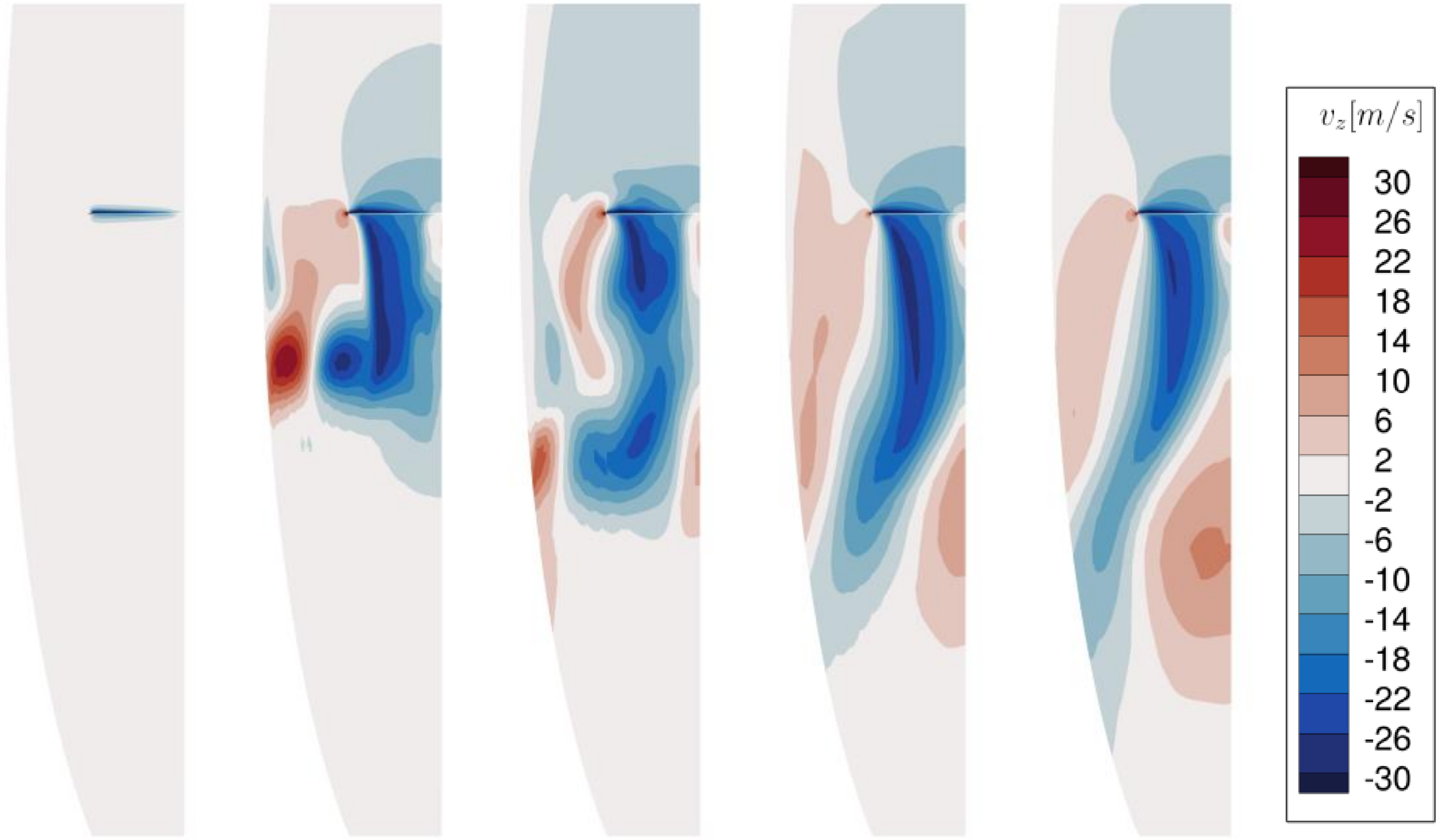
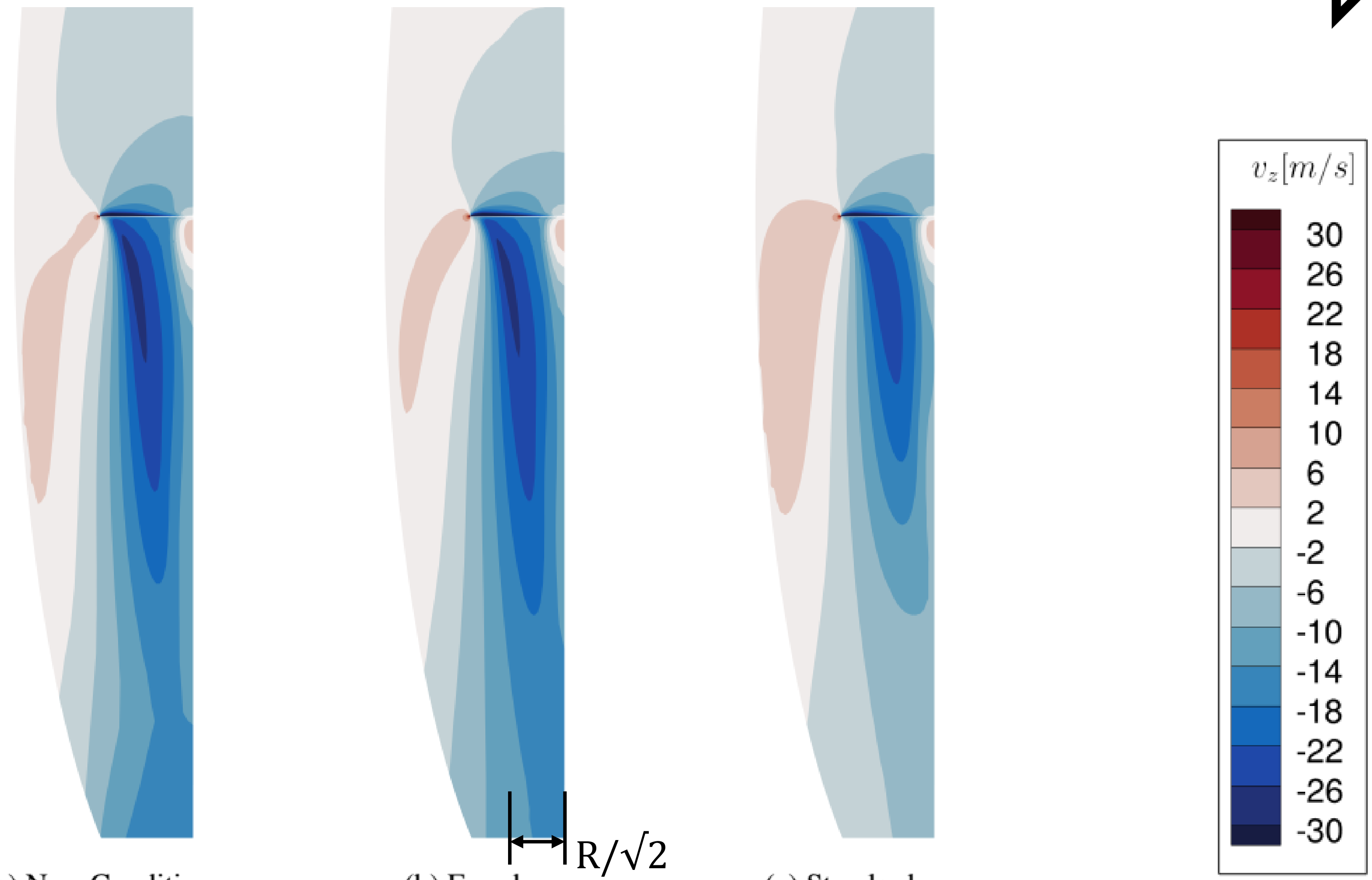
Axial Velocity Field Evolution Contour Plots

Test details:	
Grid	M2 6R
BC	Std
IC	QF
Framerate(rev)	10



Axial Velocity Field ‘Settled’ Contour Plots

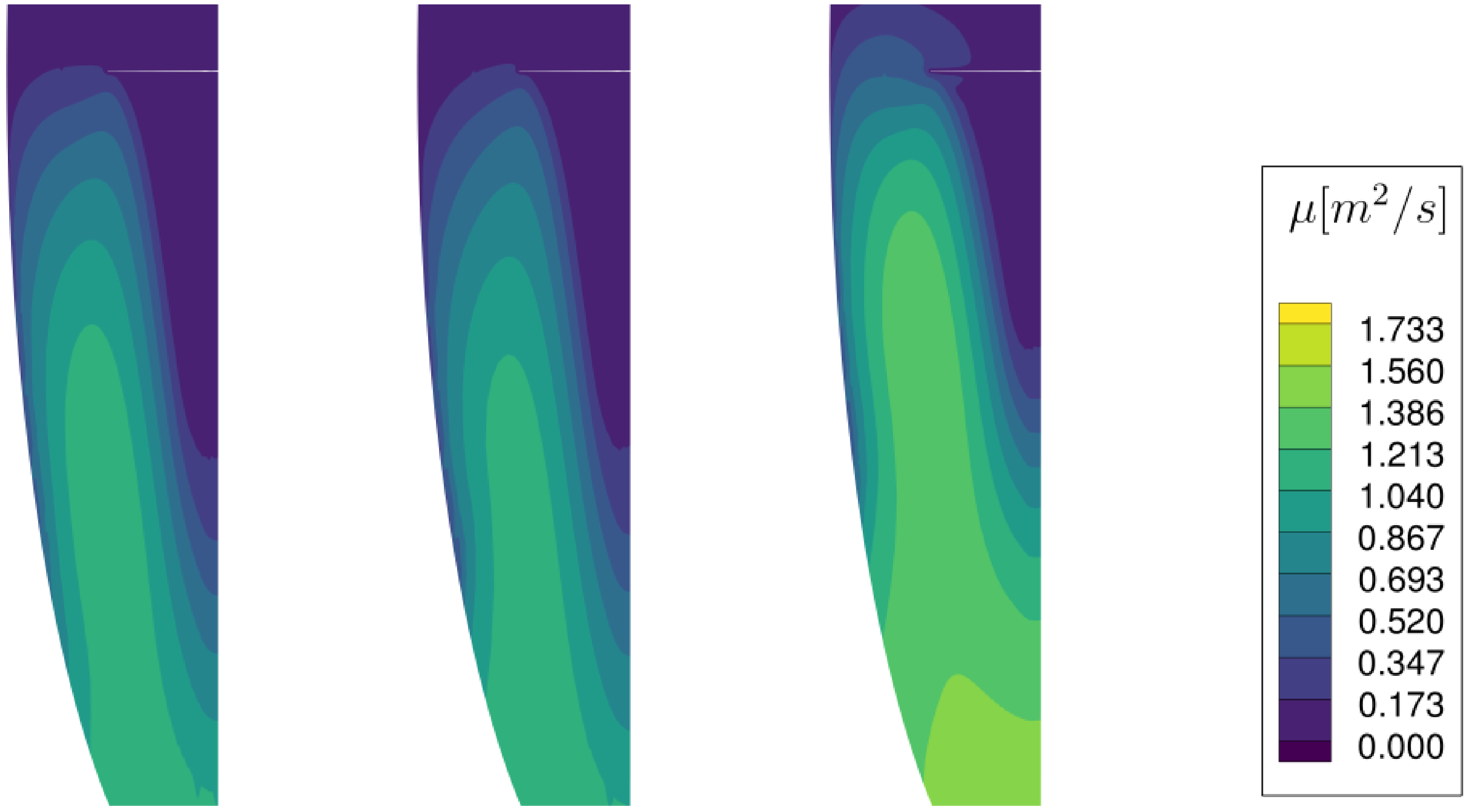
Test details:	
Grid	M2 6R
Frame(rev)	200



(a) New Condition (b) Froude (c) Standard

Eddy Viscosity Field 'Settled' Contour Plots

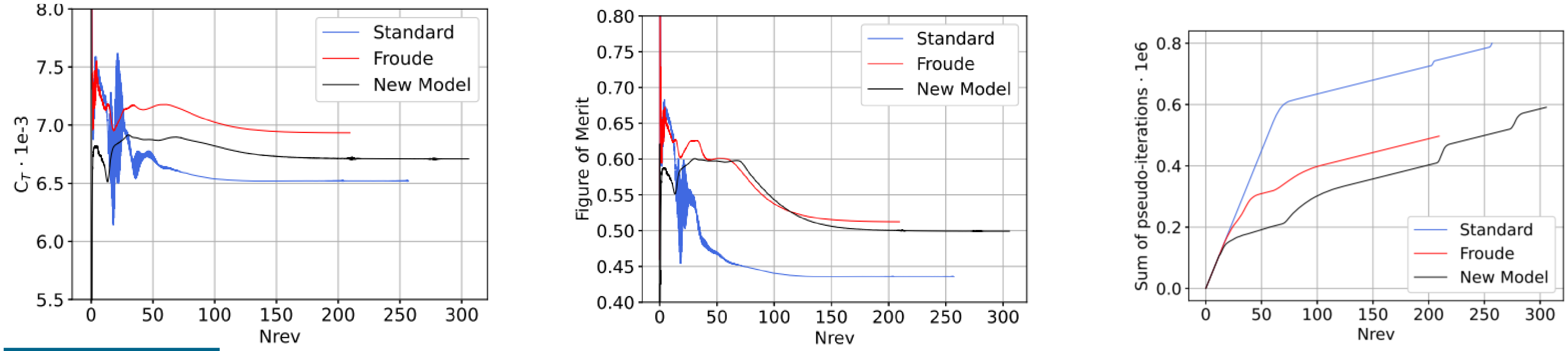
Test details:	
Frame(rev)	200



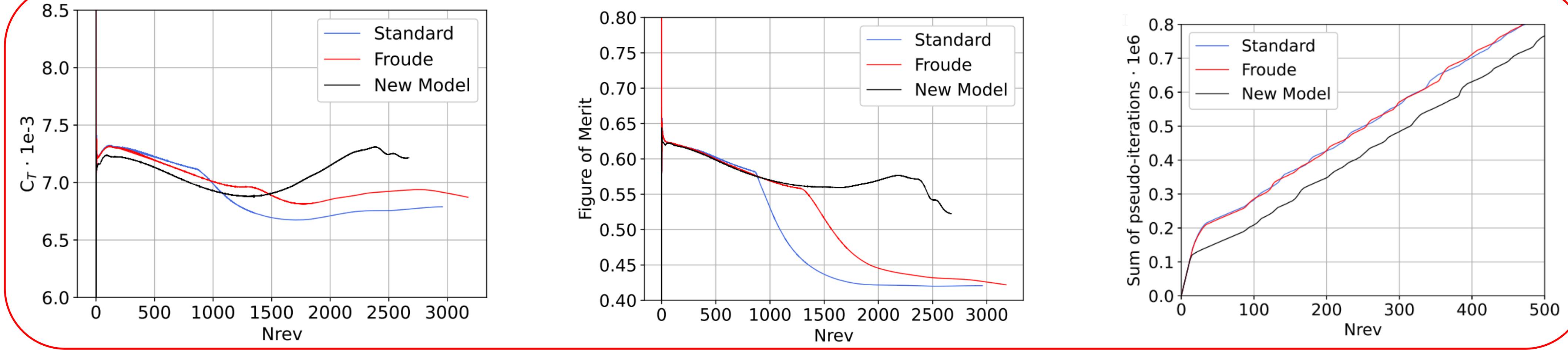
(a) New Condition (b) Froude (c) Standard

Plots of CT, FM, and pseudo-iteration sum for Monocoque Grids

M2 6R



M2 25R

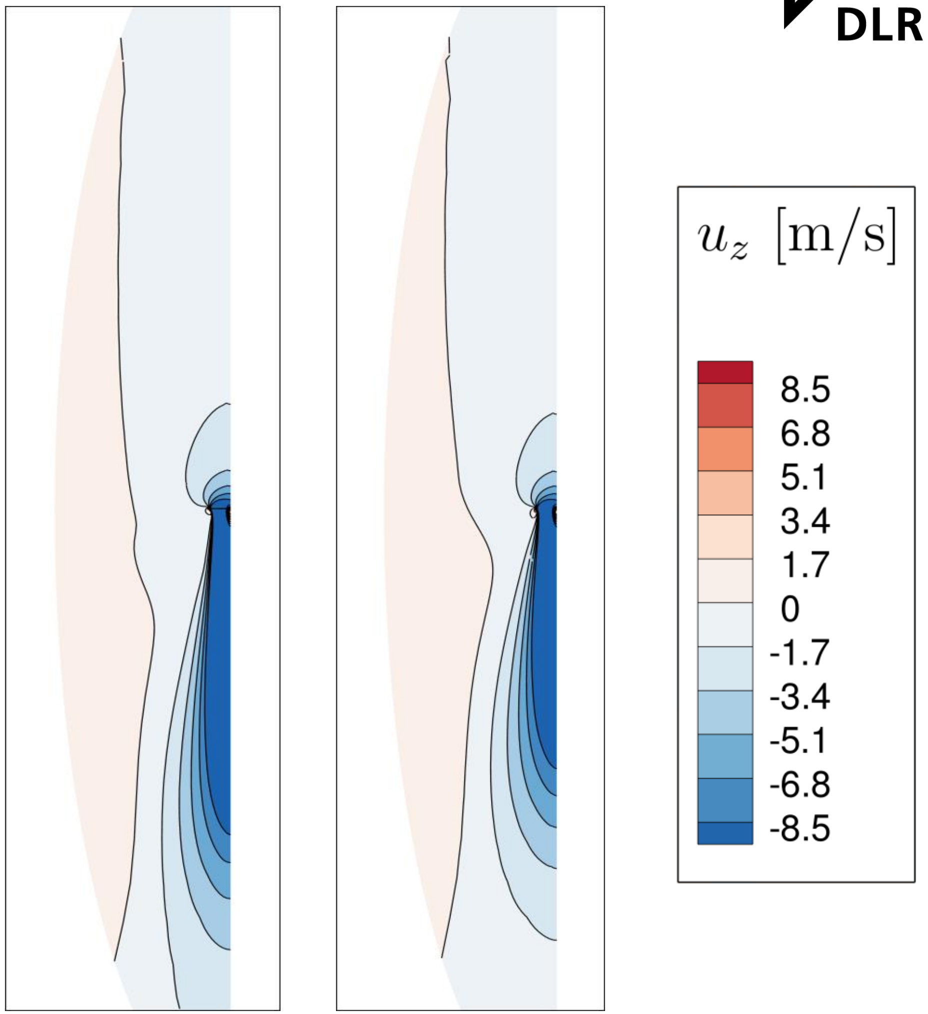


Recirculation Phenomena beyond 500 Revolutions (M2 25R)

How flow fields start…

(a) Froude **(b) Standard**

How flow fields evolve beyond 500 revolutions…



(a) Froude **(b) Standard**

Results and Conclusions

Test Type	Case	Grid used	Turbulence Model	Boundary Condition	Initial Condition	Convergence Tolerance
BC and IC condition Investigation	12	M2 25R	SA	Froude	QuiscentFlow	1E-06
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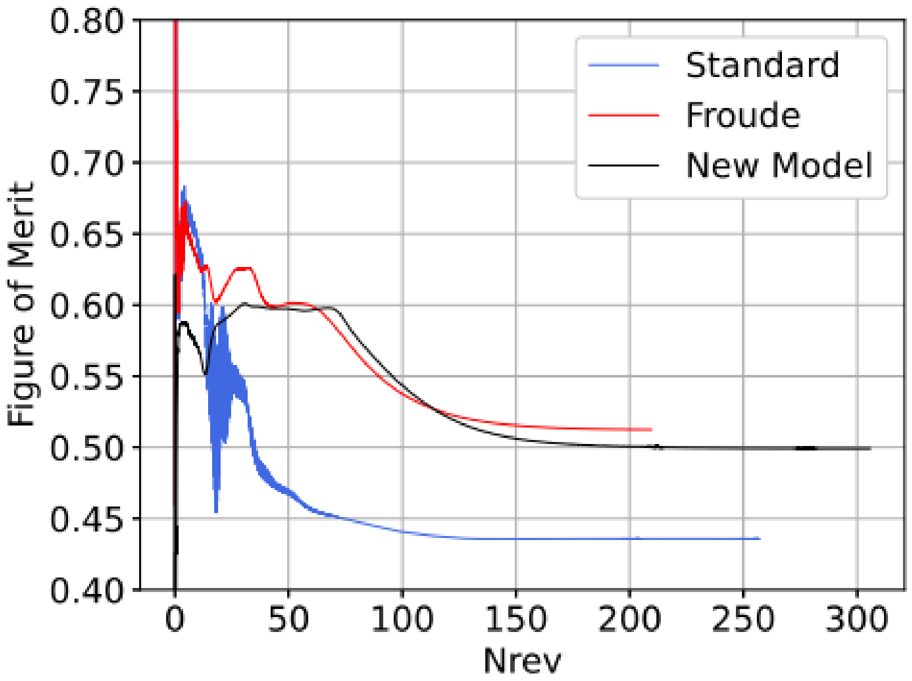
	16			Standard	QuiscentFlow	
	17			New Model	New Model	
	18	C2 6R	SA	Froude	QuiscentFlow	1E-06
	19			Standard	QuiscentFlow	
	20			New Model	New Model	
	21	C2 6R	SA	New Model	QuiscentFlow	1E-06
	22	C1 6R	SA	Froude	QuiscentFlow	1E-06
	23			Standard	QuiscentFlow	
	24			New Model	New Model	

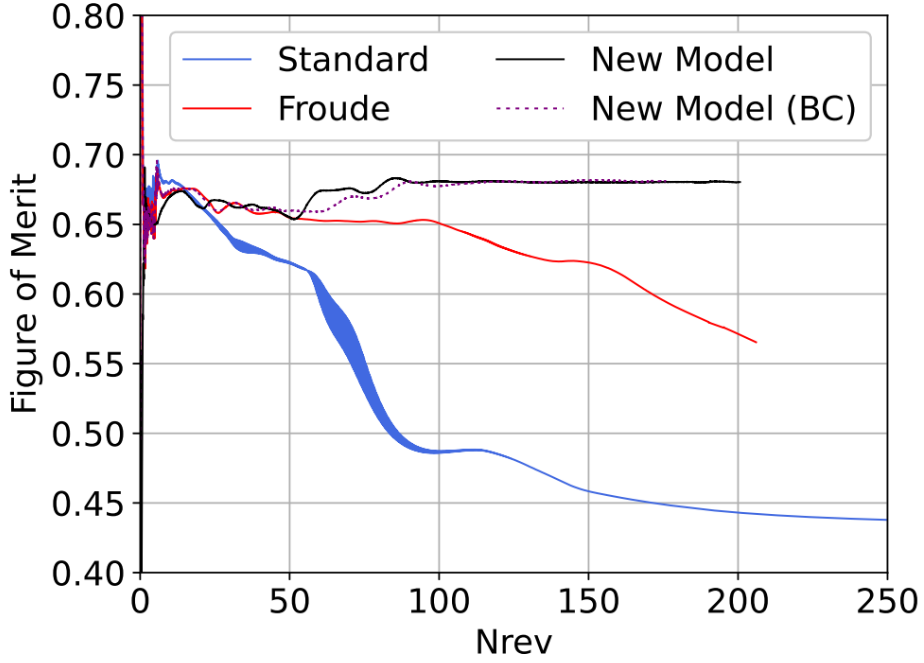
Cases 15–21: Monocoque VS Chimera in 6R domain

Plots of FM Comparison: Monocoque vs Chimera

M2 6R



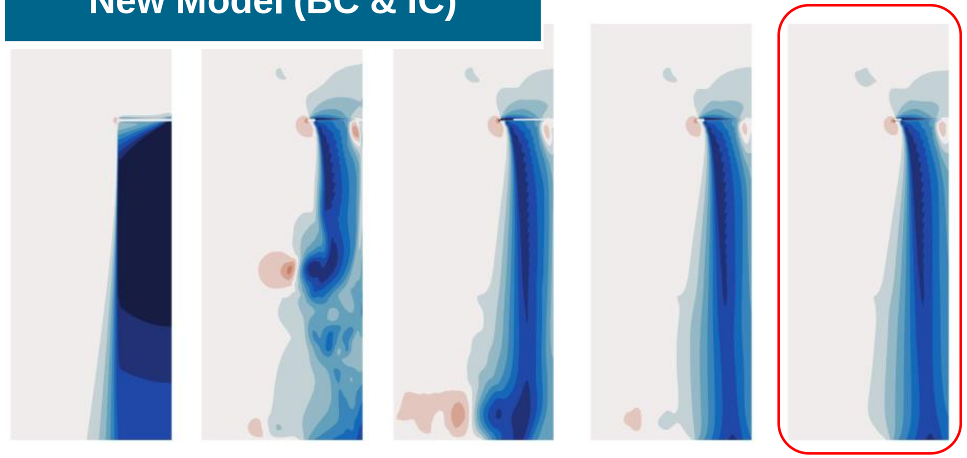
C2 6R



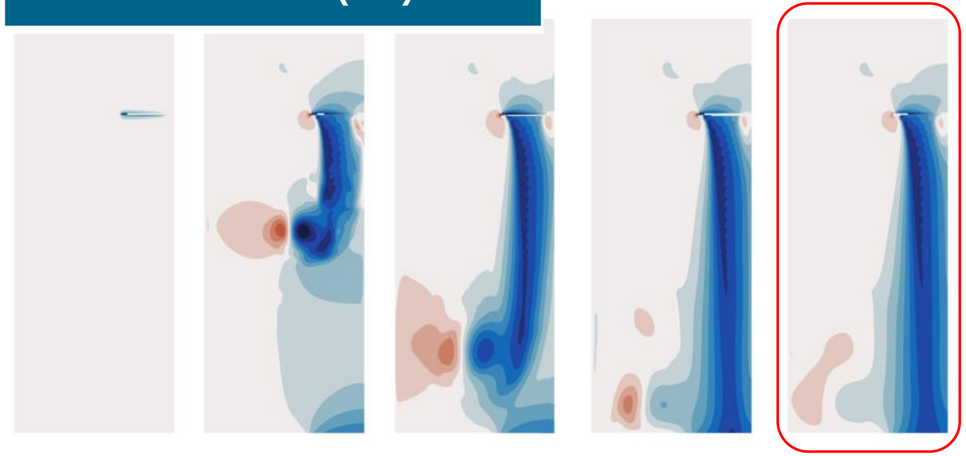
Research Motivation | Existing Boundary Conditions | New Boundary Conditions | Parametric Studies | Mesh and settings | **Results and Conclusions**

New Model (BC & IC) - vs - New Model (BC)

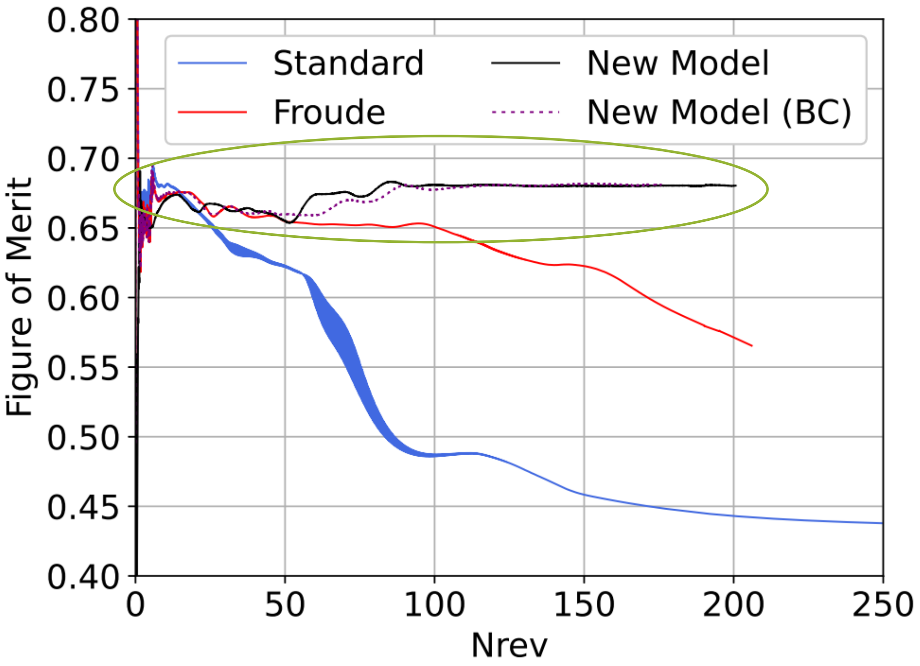
New Model (BC & IC)



New Model (BC)



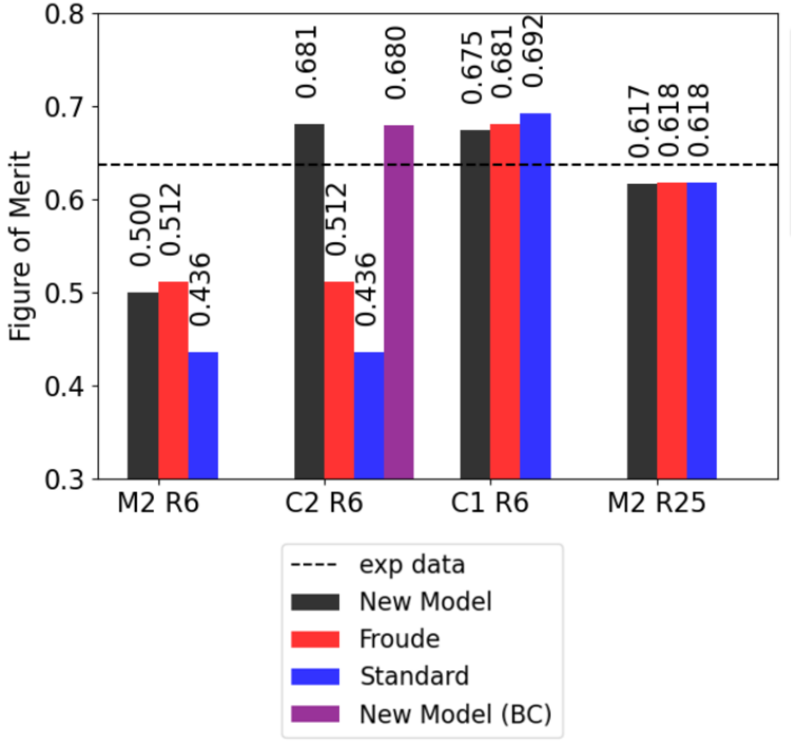
C2 6R



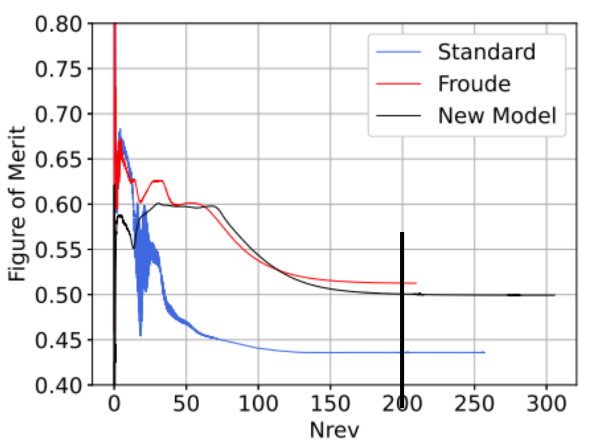
Summary

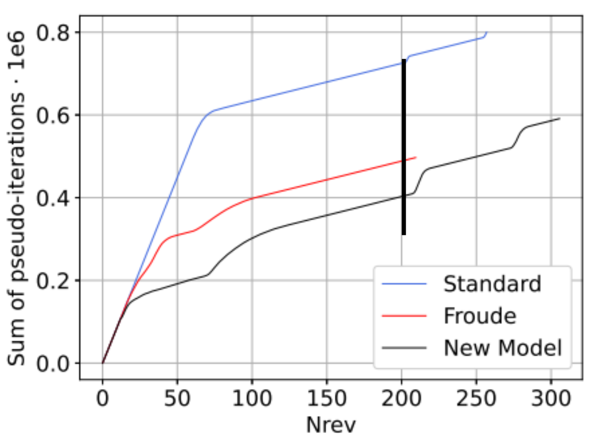
- New boundary condition is more robust
- Initialization aids in faster convergence
- New boundary condition seems to be aiding simulation reach it's 'steady state' when regarding the number of inner iterations

FM comparison from different tests



Less inner iterations required





References

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2. F. Jia, Q. Wang, and P. Spalart. “Improved Initial and Boundary Conditions for Hovering Rotor CFD Simulations”. In: Vertical Flight Society’s 78th Annual Forum (June 2022). DOI: 10.4050/F-0078-2022-17474.
3. S. YOON, L. CHANG, and D. KWAK. “LU-SGS implicit algorithm for three-dimensional incompressible Navier-Stokes equations with source term”. In: 9th Computational Fluid Dynamics Conference. DOI: 10.2514/6.1989-1964.
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5. J. Dacles-Mariani, J. Dacles-Mariani, D. Kwak, et al. “On numerical errors and turbulence modeling in tip vortex flow prediction”. In: International Journal for Numerical Methods in Fluids 30 (1999), pp. 65–82.
6. M. Smith, J. Lim, B. Wall, et al. “An assessment of CFD/CSD prediction state-of-the-art using the HART II International Workshop data”. In: Annual Forum Proceedings - AHS International 1 (May 2012), pp. 1–41.

Complimentary Material

New/Contemporary Boundary Conditions

Jia's Modified Version of the Spalart Model Supplementary Equations

Cartesian Components

$$u_x = u_r \frac{x}{\sqrt{x^2+y^2+z^2}} - u_\theta \frac{z}{\sqrt{x^2+y^2+z^2}} \frac{x}{\sqrt{x^2+y^2}}$$

$$u_y = u_r \frac{y}{\sqrt{x^2+y^2+z^2}} - u_\theta \frac{z}{\sqrt{x^2+y^2+z^2}} \frac{y}{\sqrt{x^2+y^2}}$$

$$u_z = u_r \frac{z}{\sqrt{x^2+y^2+z^2}} + u_\theta \frac{\sqrt{x^2+y^2}}{\sqrt{x^2+y^2+z^2}}$$

Spherical Components

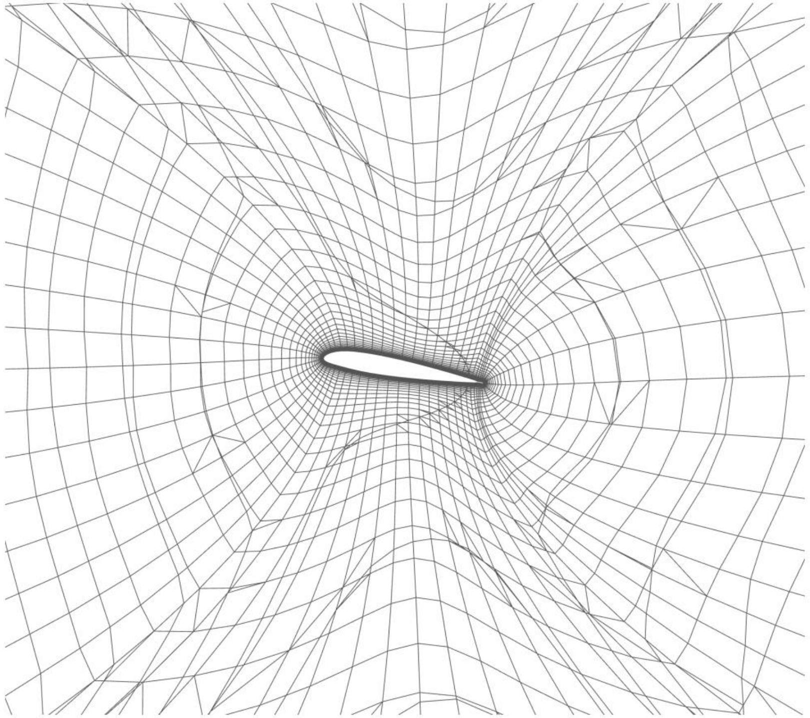
$$u_r = \frac{-A}{r_m}\sqrt{\frac{T}{\rho}}\left[f_m(\theta_m) + \tan\left(\frac{\theta_m}{2}\right)\frac{\mathrm{d}\theta_m}{\mathrm{d}\theta}\bigg|_{\theta_m}\right]$$

$$u_\theta = \frac{A}{r_m}\sqrt{\frac{T}{\rho}}\tan\left(\frac{\theta_m}{2}\right) f_m(\theta_m)$$

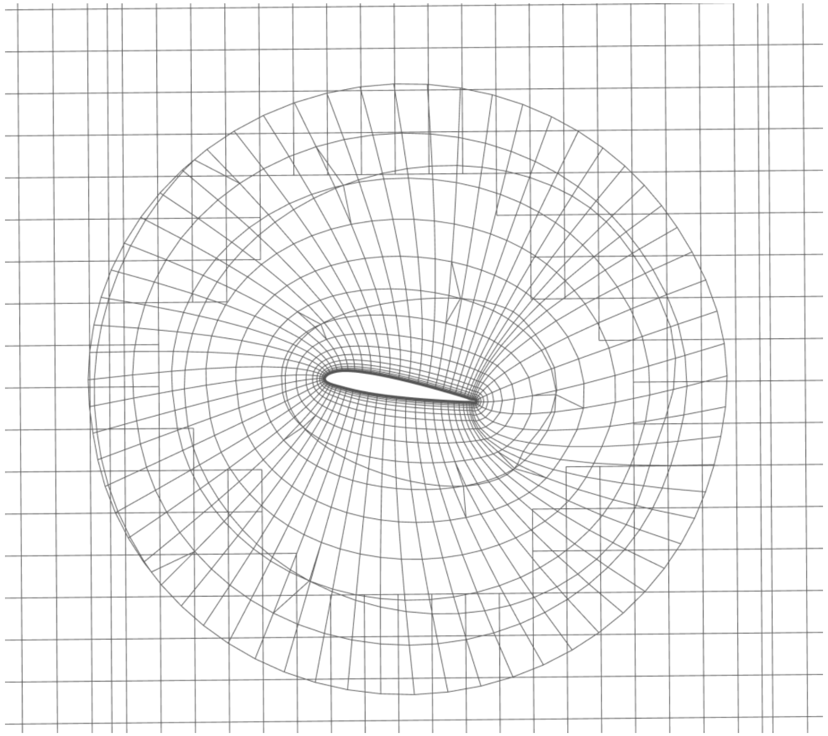
Mesh and Settings

Blade cross-sectional view

Monocoque



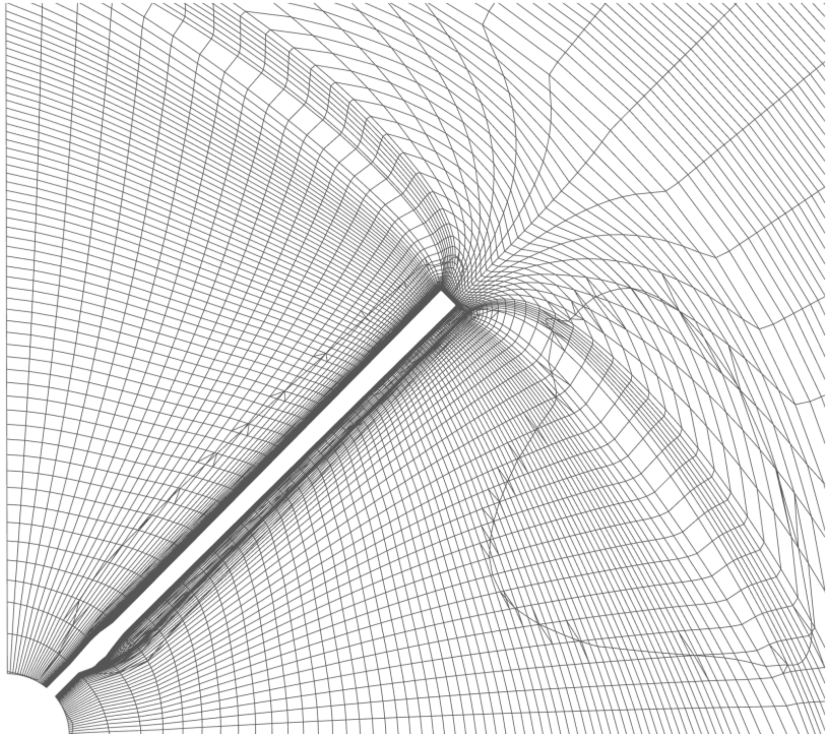
Chimera



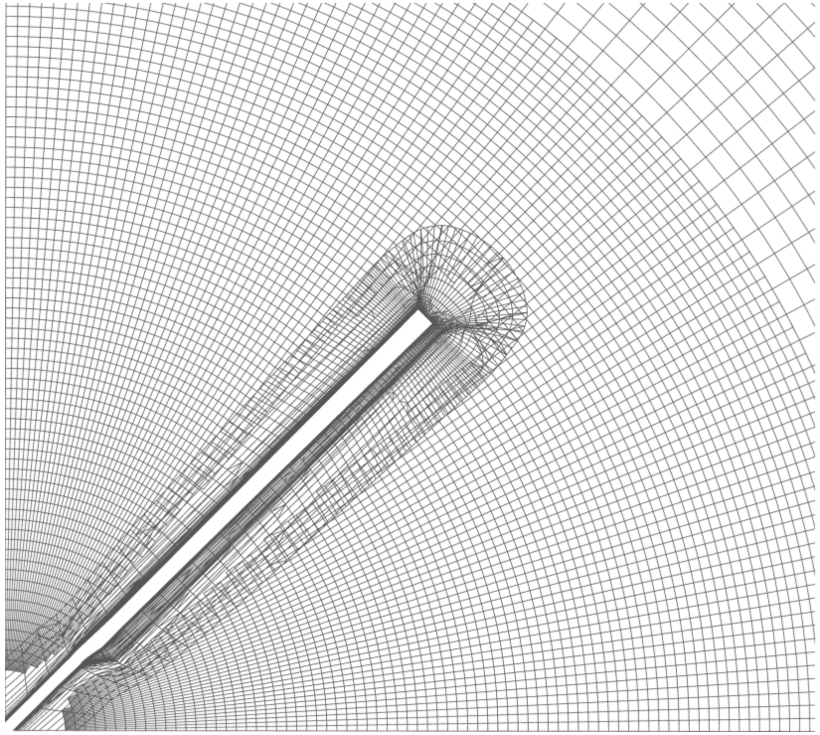
Mesh and Settings

Blade top-down view

Monocoque



Chimera



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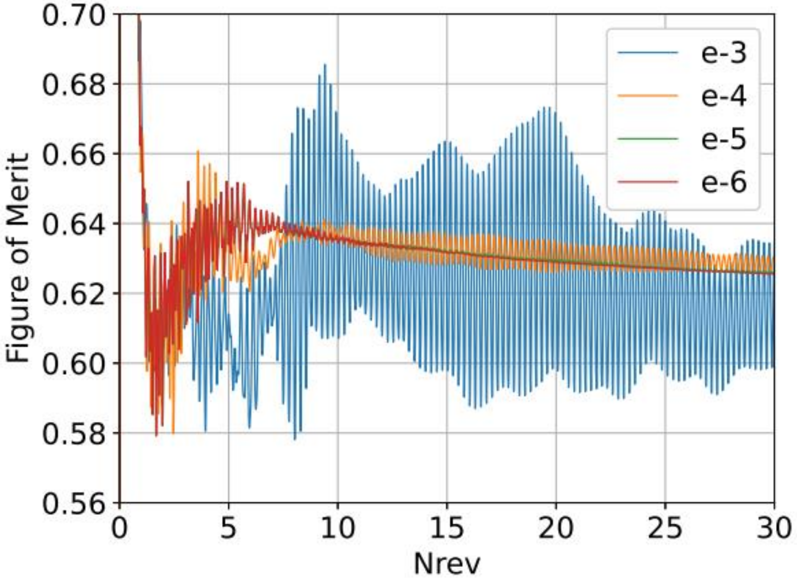
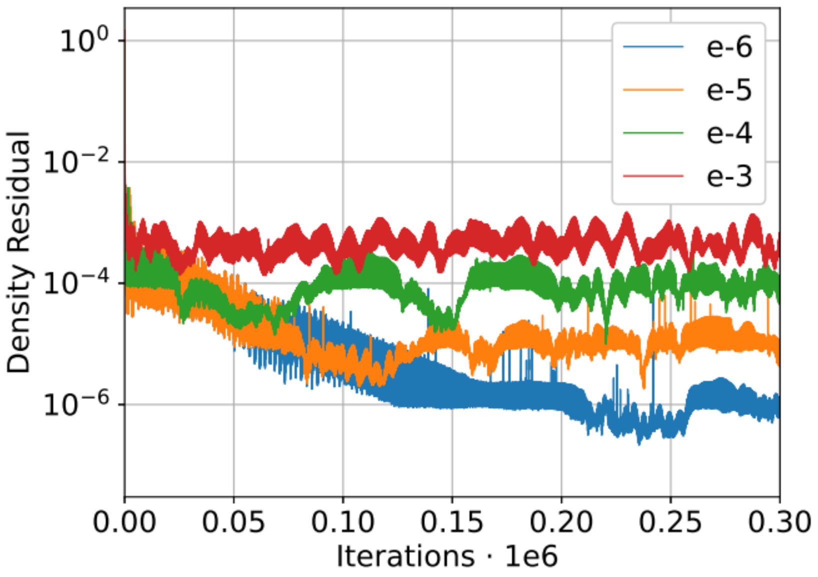
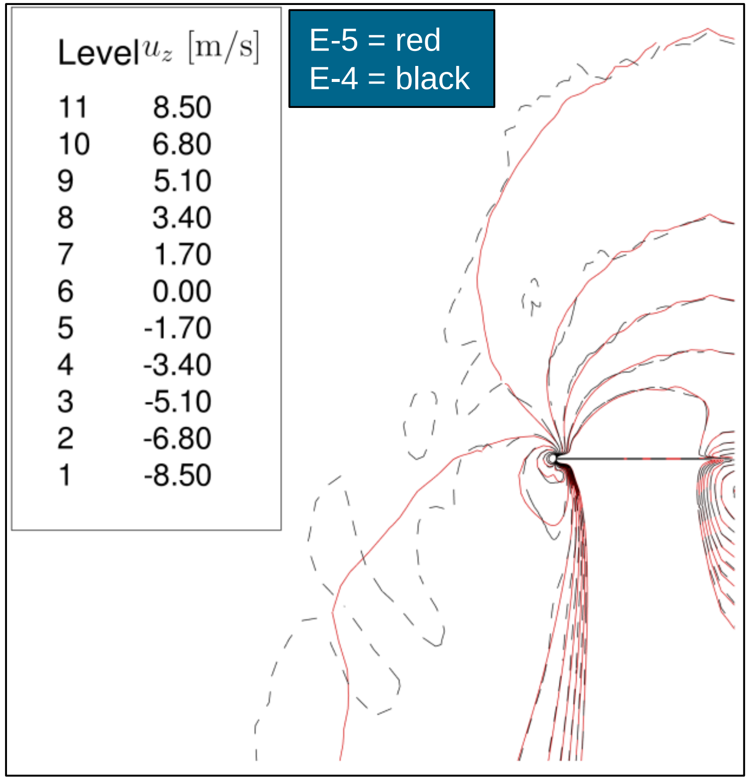
Parametric Studies

Convergence Criteria Tests Plots







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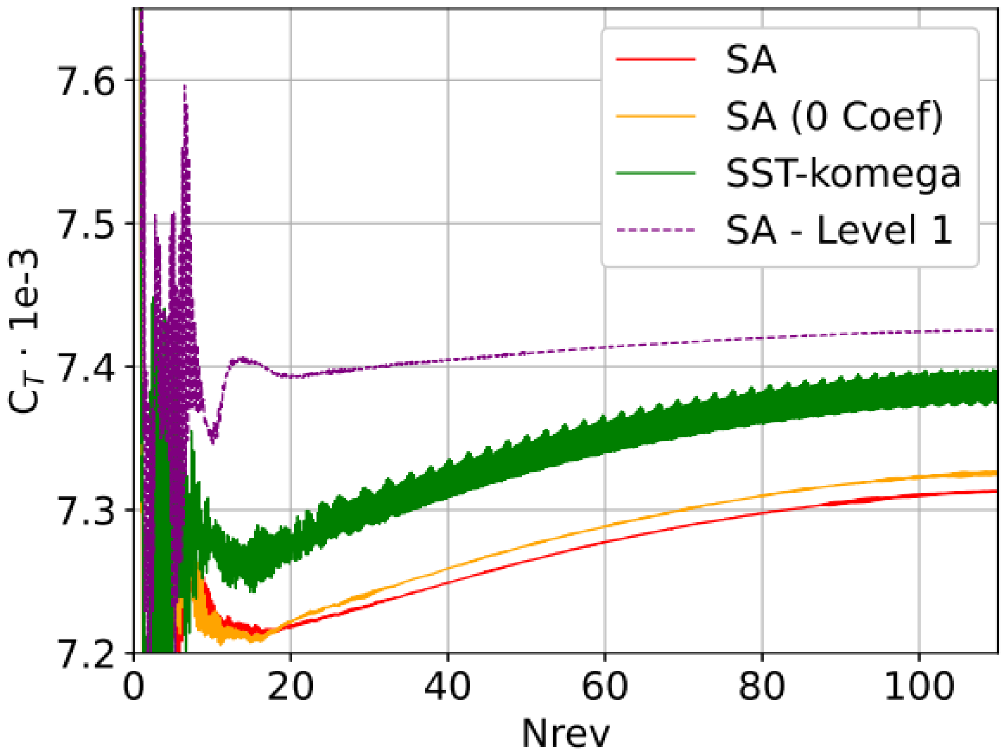
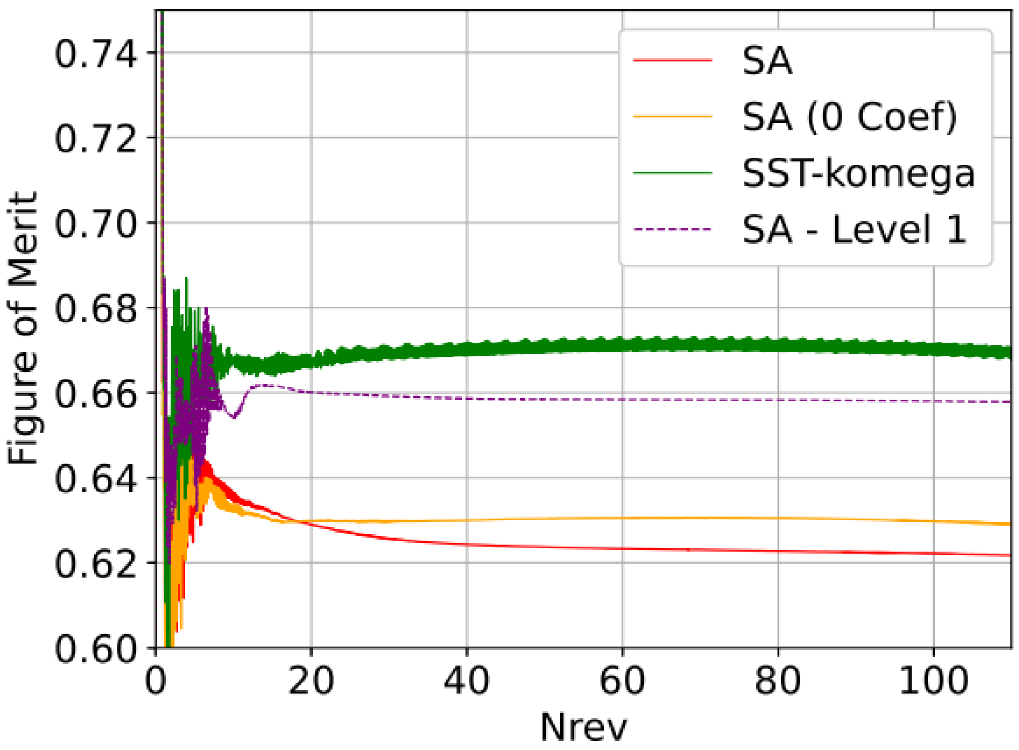
Parametric Studies

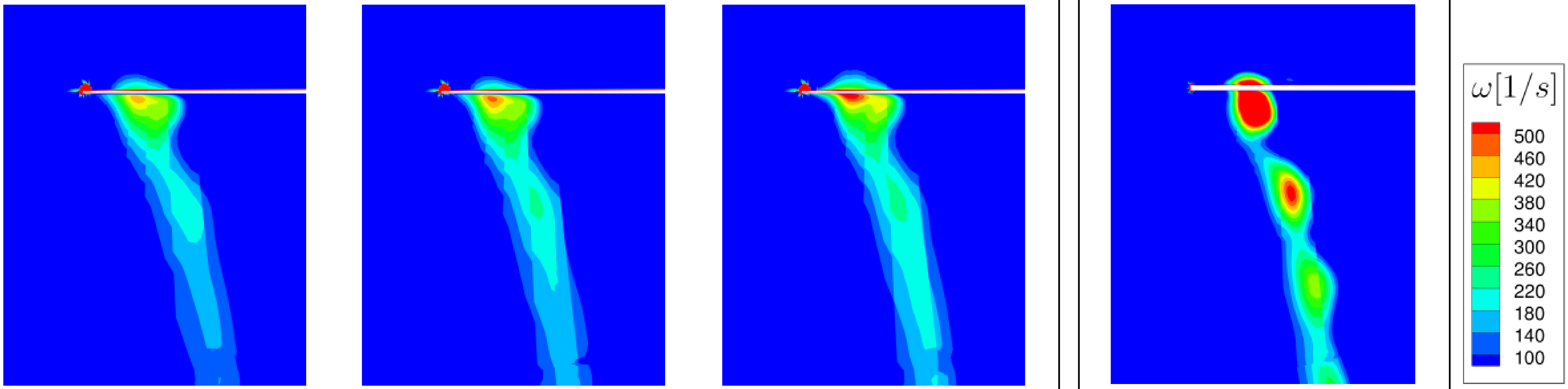
Turbulence Model Tests Plots





Parametric Studies

Turbulence Model Blade Tip Vorticity Plots



(a) SA | (b) SA (0 Coef) | (c) SST | (d) SA

Level 2 mesh

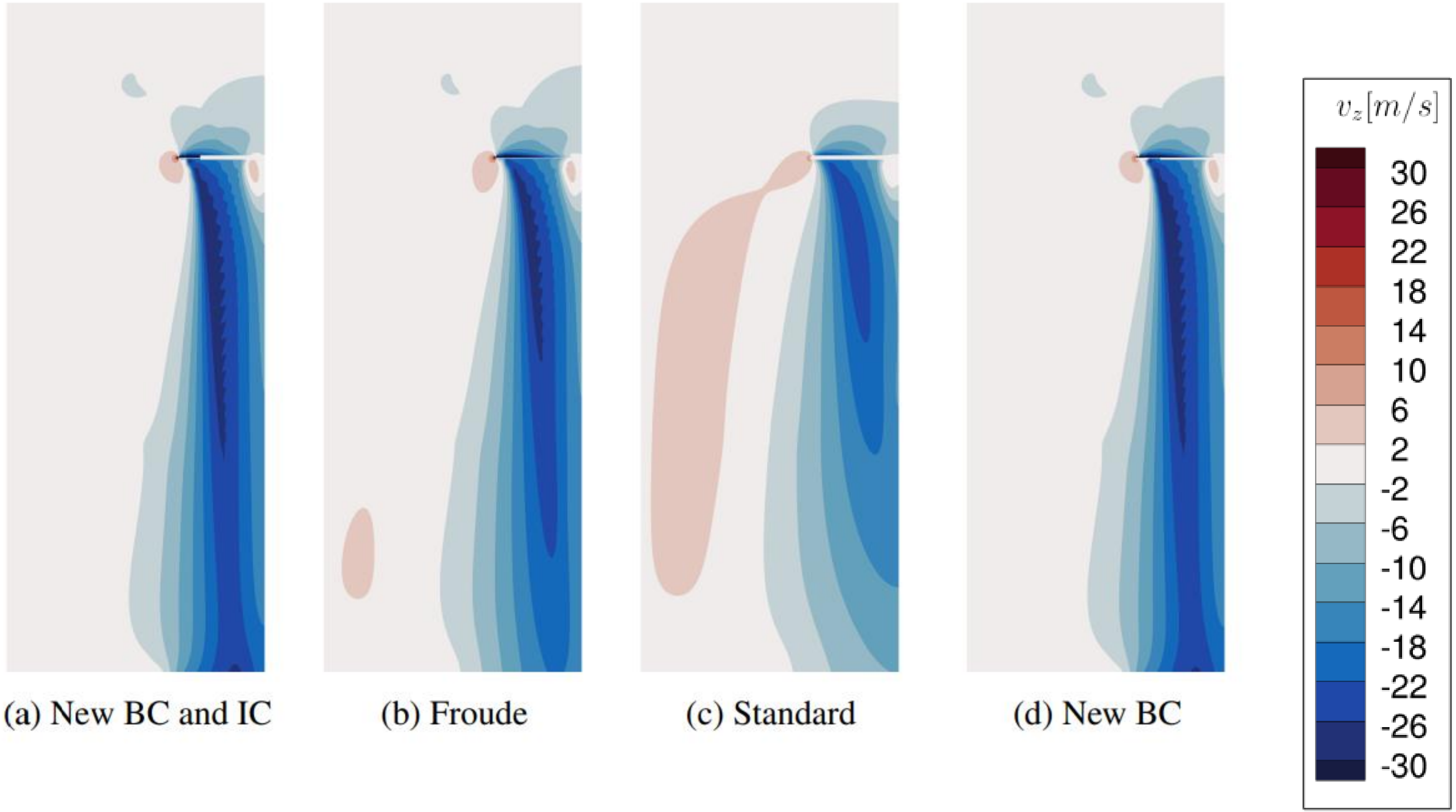
Level 1 mesh

Axial Velocity Contour Plots (C2 R6)

DLR

Test details:

Grid	C2 6R
Frame(rev)	200



(a) New BC and IC (b) Froude (c) Standard (d) New BC