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GERO
GRUPO DE ENERGIA RENOVÁVEL NO OCEANO

URANS simulations of a horizontal axis wind turbine under stall condition using Reynolds stress turbulence models

Candidate: Mojtaba Maali Amiri

Supervisor: Prof. Segen F. Estefen

July 2020

Outline:

COPPE UFRJ Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia GERO CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico

Problem Definition:

Evolution of the wind turbine size:

P. Veers (2019), J. O'Brien et al. (2017), W. Zhang et al. (2012), Hansen and Madsen (2011), E. Echavarria (2009)

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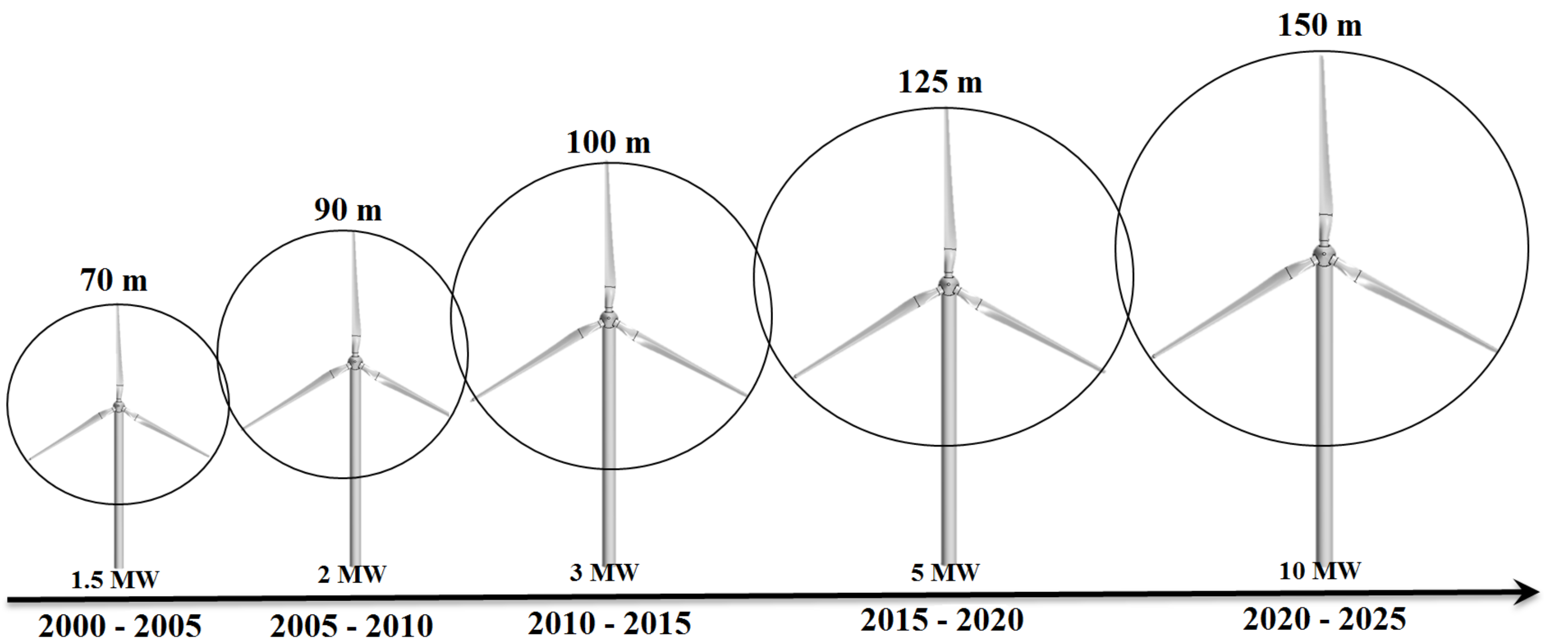

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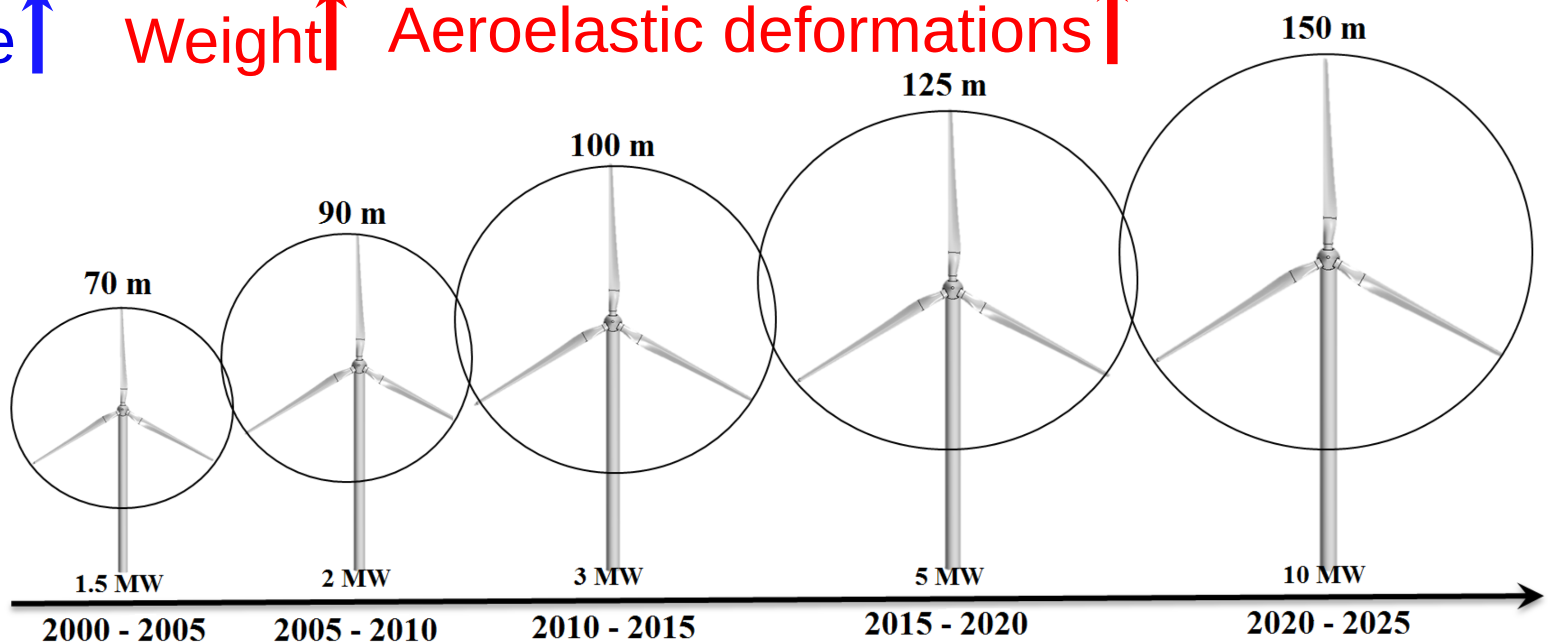
Evolution of the wind turbine size:

Size ↑ Weight ↑ Aeroelastic deformations ↑



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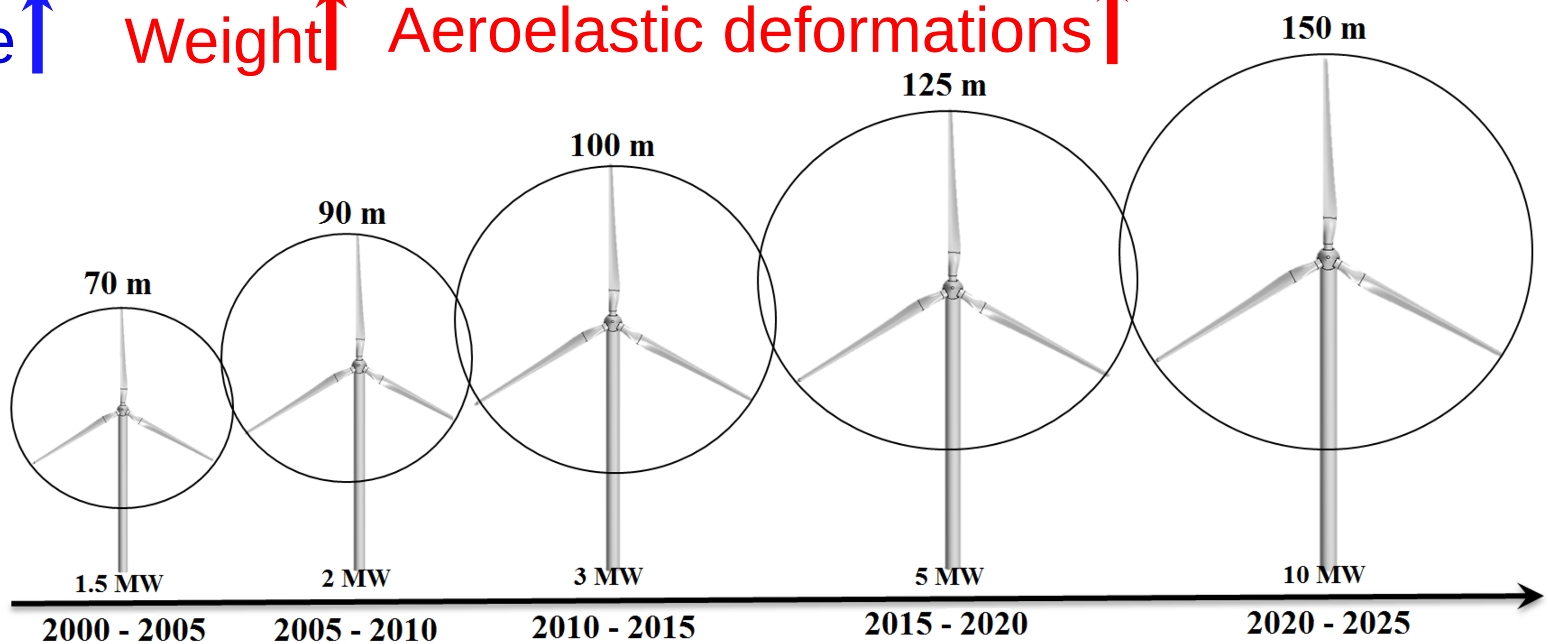

Modeling accuracy of the turbulent flow around the wind turbine rotors

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Problem Definition:

Modeling the turbulent flow around a wind turbine:

$$\frac{\partial(\rho U_i)}{\partial t} + \frac{\partial(\rho U_j U_i)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial(2\mu S_{ij})}{\partial x_j}$$

C. Argyropoulos and N. Markatos (2015)

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2. Nonlinear quadratic and cubic turbulent eddy viscosity models
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↑ Computational cost

And

Accuracy

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The choice of a proper turbulence model is a compromise between the accuracy and the computational effort.

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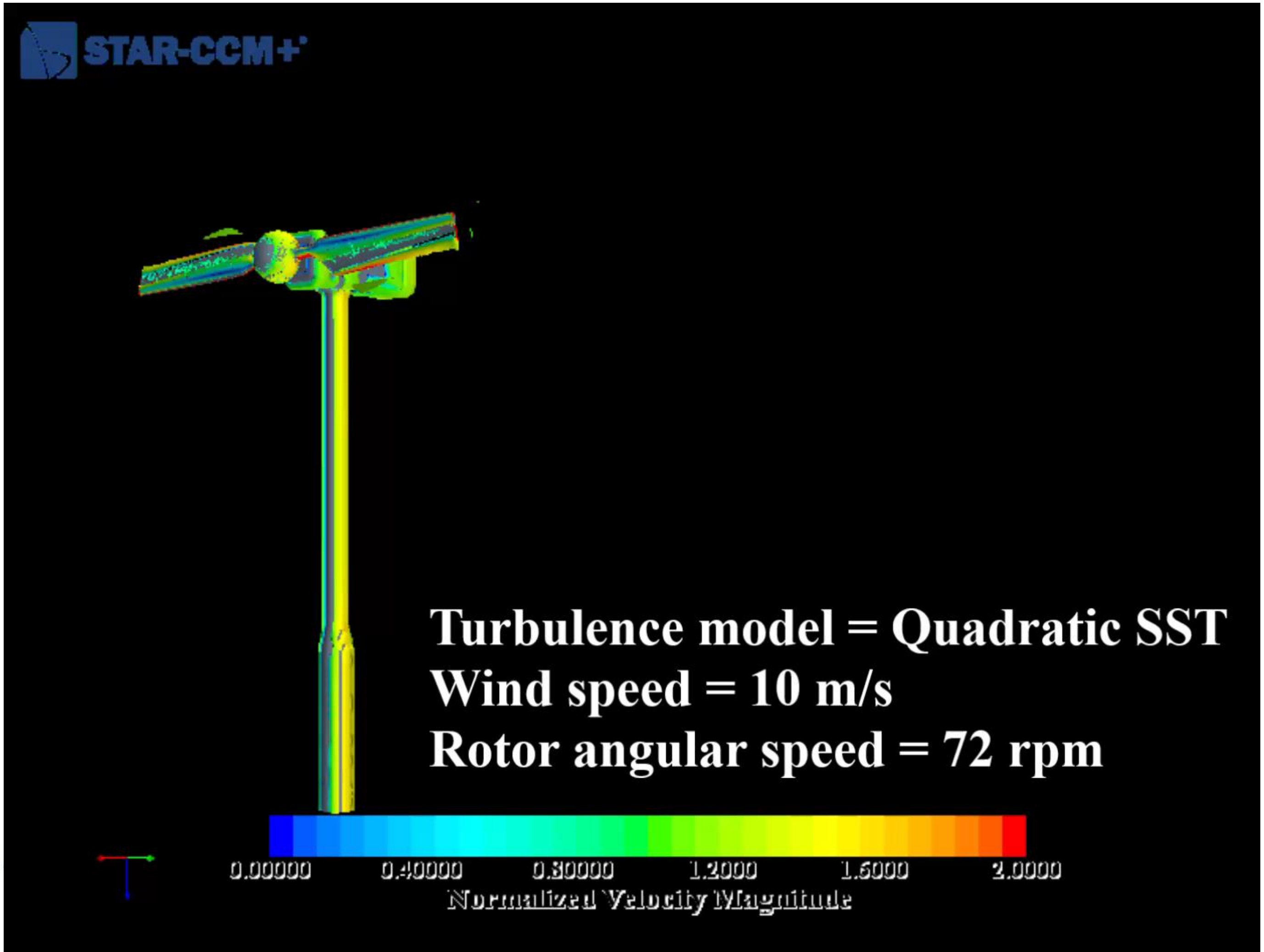

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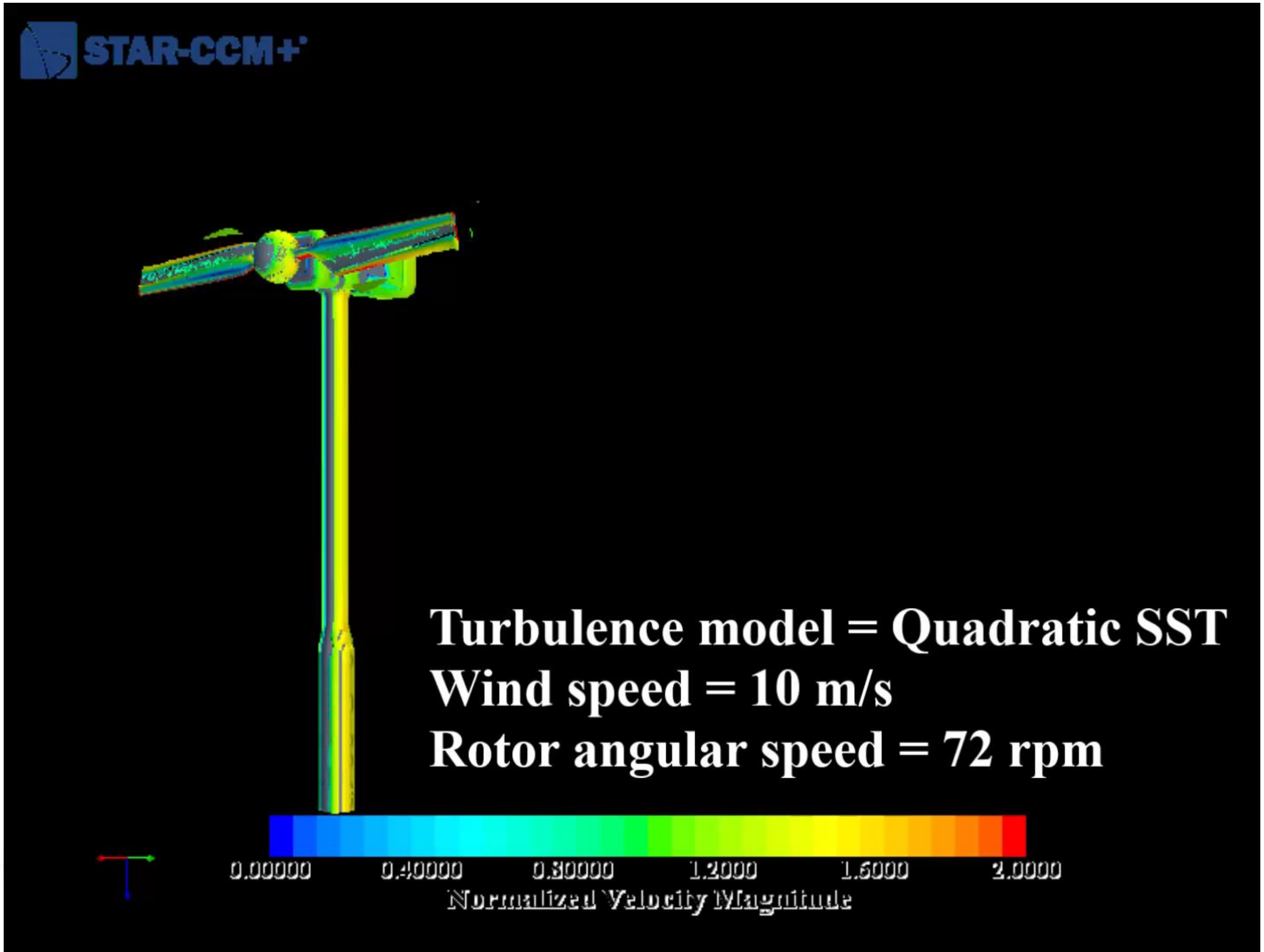
Problem Definition:

Correct prediction of the turbulent flow characteristics around wind turbines operating under stall condition



Scope of the Present Work:

- Evaluation of the capabilities of five URANS-based turbulence models to predict the turbulent flow characteristics around a horizontal axis wind turbine operating under stall condition.

Literature Review:

The use of nonlinear eddy viscosity and Reynolds stress turbulence models

S. A. Abdulqadir et al. (2017)

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The use of nonlinear eddy viscosity and Reynolds stress turbulence models

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F. Carneiro (2019), H. Wang et al. (2019), H. Rahimi et al. (2018),
A. Ebrahimi and M. Movahhedi (2018), M. Moshfeghi et al. (2017), H. Rahimi et al. (2016),
M. Nobari et al. (2016), M. Make and G. Vaz (2015), S. Guntur and N. N. Sørensen (2015),
L. Daroczy (2015), J. Y. You et al. (2013), Q. Wang et al. (2012), G. Yu et al. (2011),
N. Tachos (2010), A. Spentzos et al. (2007), N. N. Sørensen et al. (2002), H. Snel (1998, 2003),

linear $k-\omega$ SST

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Literature Review:

The use of nonlinear eddy viscosity and Reynolds stress turbulence models

S. A. Abdulqadir et al. (2017)

1. The latest formulations of the turbulence models are not considered.
2. Lack of detailed information about the computational cost of each turbulence model.
3. It neglects the influence of the tower.

Research Objectives:

- Extending the knowledge of the turbulent flow characteristics around horizontal axis wind turbines.

- Assessing the performance of five URANS turbulence models, principally Reynolds stress models, in predicting the wind turbines aerodynamics under stall condition.

Numerical Model:

Numerical Model:

- STARCCM+ is used.
- Modeling the fluid flow:

$$\frac{\partial(\rho U_i)}{\partial t} + \frac{\partial(\rho U_j U_i)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial(2\mu S_{ij} + \tau_{ij})}{\partial x_j},$$

with continuity:

$$\frac{\partial U_i}{\partial x_i} = 0,$$

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1.1. Linear pressure-strain model (LRST)
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2. SST k-w turbulence model
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with continuity:

$$\frac{\partial U_i}{\partial x_i} = 0,$$

$$\tau_{ij} = 2\mu_t S_{ij} - \frac{2}{3}\rho k \delta_{ij},$$

Boussinesq's hypothesis

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An alignment between the Reynolds stresses and the mean deformation rate of the flow.

$$\gamma_\tau = \text{atan}\left\{\frac{\tau_{23}}{\tau_{12}}\right\}, \qquad \gamma_g = \text{atan}\left\{\frac{\frac{\partial U_2}{\partial x_3} + \frac{\partial U_3}{\partial x_2}}{\frac{\partial U_1}{\partial x_2} + \frac{\partial U_2}{\partial x_1}}\right\},$$

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with continuity:

$$\frac{\partial U_i}{\partial x_i} = 0,$$

$$\tau_{ij} = 2\mu_t S_{ij} - \frac{2}{3}\rho k \delta_{ij} - 2\times 0.04645\mu_t \left(O_{ij}.S_{ij} - S_{ij}.O_{ij}\right),$$

$$O_{ij} = \frac{\Omega_{ij}}{\sqrt{(S_{ij} - \Omega_{ij})(S_{ij} - \Omega_{ij})}},$$

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$$\frac{\partial(\tau_{ij})}{\partial t} + \nabla.\left(\tau_{ij}.U\right) = \nabla.\left[\mu + \frac{\mu_t}{\sigma_k}\right]\frac{\nabla\tau_{ij}}{\rho} + P_{ij} - \frac{2}{3}\varepsilon\mathbf{I} + \Pi_{ij},$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla.(\rho\varepsilon U) = \nabla.\left[\mu + \mu_t\sigma_k\right]\nabla\varepsilon + \frac{\varepsilon}{k}\left[C_{\varepsilon 1}\left(\frac{1}{2}tr(P_{ij})\right) - C_{\varepsilon 2}\rho\varepsilon\right],$$

STARCCM+ (2017)

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turbulent pressure-strain interaction

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla.(\rho\varepsilon U) =$$

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$$\Pi = \Pi_s + \Pi_r + \Pi_w.$$

STARCCM+ (2017), B. E. Launder, N. Shima (1989)

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$$\Pi_{ij} = -\left[C_{s1}\rho\varepsilon + C_{r4}tr(P)\right]A_{ij} + C_{s2}\rho\varepsilon\left(A_{ik}A_{kj} - \frac{1}{3}A_{mn}A_{mn}\delta_{ij}\right) + \left(C_{r3} - C^*_{r3}\sqrt{A_{ij}A_{ij}}\right)\rho k S_{ij} + C_{r1}\rho k\left(A_{ik}S_{jk} + S_{ik}A_{jk} - \frac{2}{3}A_{mn}S_{mn}\delta_{ij}\right) + C_{r2}\rho k\left(A_{ik}\Omega_{jk} + \Omega_{ik}A_{jk}\right),$$

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Anisotropy Tensor

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$$\Pi - \varepsilon = \left(1 - \alpha^3\right)\left(\Pi^w - \varepsilon^w\right) + \alpha^3\left(\Pi^h - \varepsilon^h\right)$$

blending parameter

STARCCM+ (2017), B. E. Launder, N. Shima (1989), C. G. Speziale et al. (1991), P. Durbin, (1993), S. Lardeau, R. Manceau (2014)

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2. SST k-w turbulence model

2.1

2.2

$$\Pi^h{}_{ij} = -\left[C_1\rho\varepsilon + C_{1s}tr(P)\right]A_{ij} + \left(C_3 - C_{3s}\sqrt{A_{ij}A_{ij}}\right)\rho k S_{ij} + C_4\rho k\left(A_{ik}S_{jk} + S_{ik}A_{jk} - \frac{2}{3}A_{mn}S_{mn}\delta_{ij}\right) + C_5\rho k\left(A_{ik}\Omega_{jk} + \Omega_{ik}A_{jk}\right).$$

$$\Pi^w{}_{ij} = 5\frac{\varepsilon}{k}\left[\frac{\tau_{ik}}{\rho}n_j n_k + \frac{\tau_{jk}}{\rho}n_i n_k - \frac{1}{2}\frac{\tau_{kl}}{\rho}n_k n_l\left(n_i n_j + \delta_{ij}\right)\right]$$

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with continuity:

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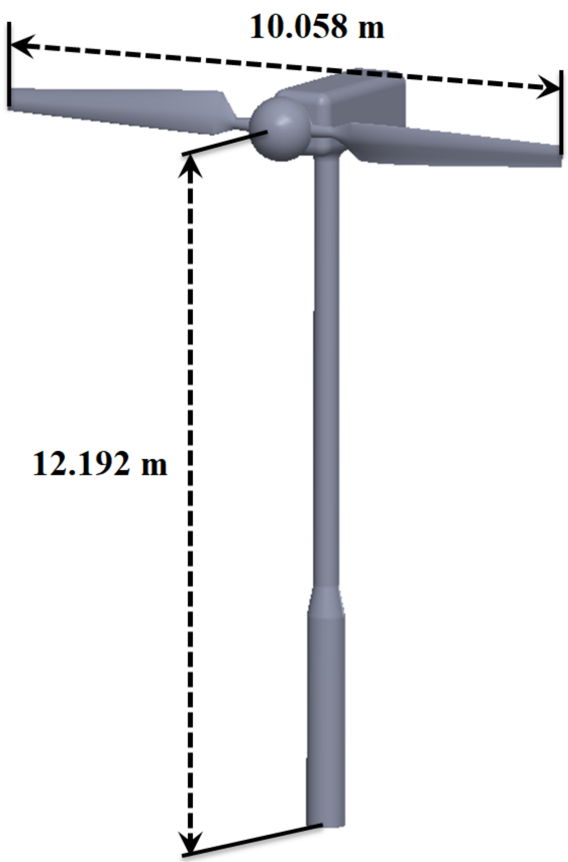
- Discretization schemes:
  - Second-order schemes for convective and diffusion terms.
  - Second-order implicit scheme for transient term.
- A SIMPLE-type solver is used for pressure-velocity coupling
- The simulations are performed for four rotor revolutions.

Geometry and Computational Conditions:

- The NREL phase VI horizontal axis wind turbine

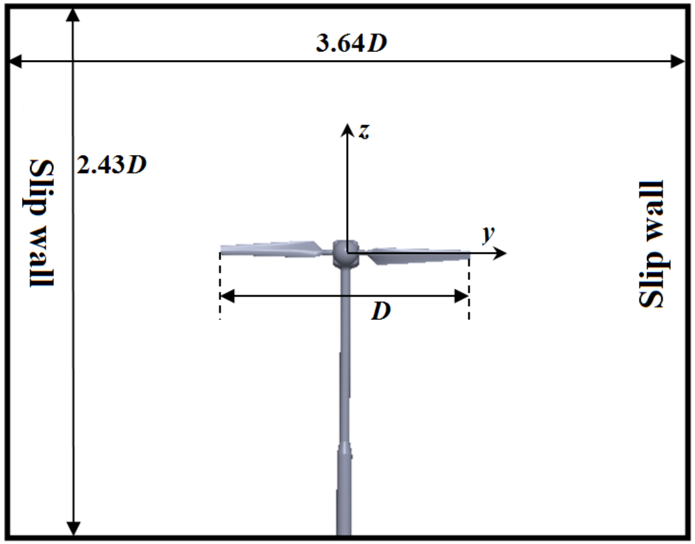


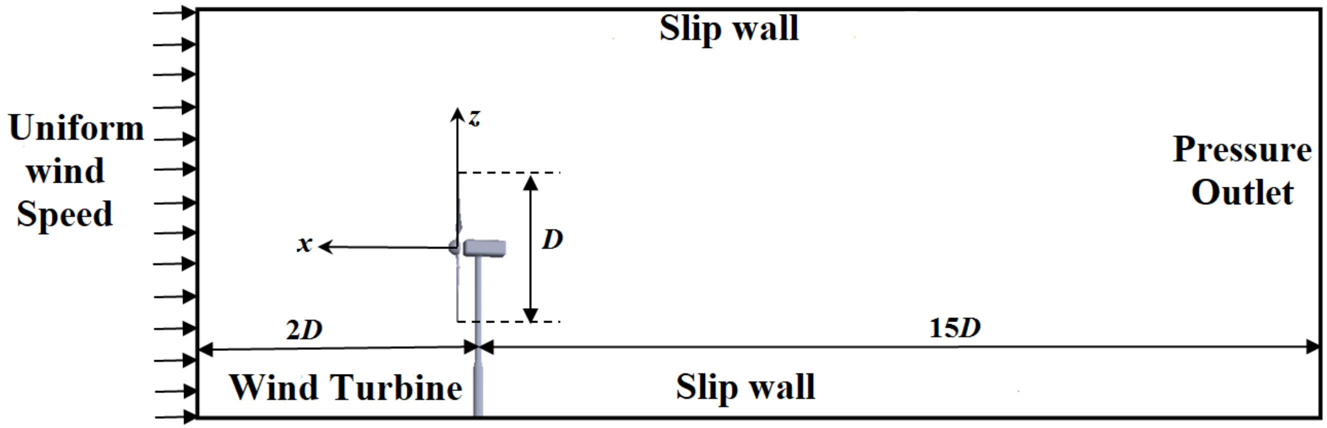
P. Giguere, M. Selig (1999), M. Hand et al. (2001)

Computational Conditions:

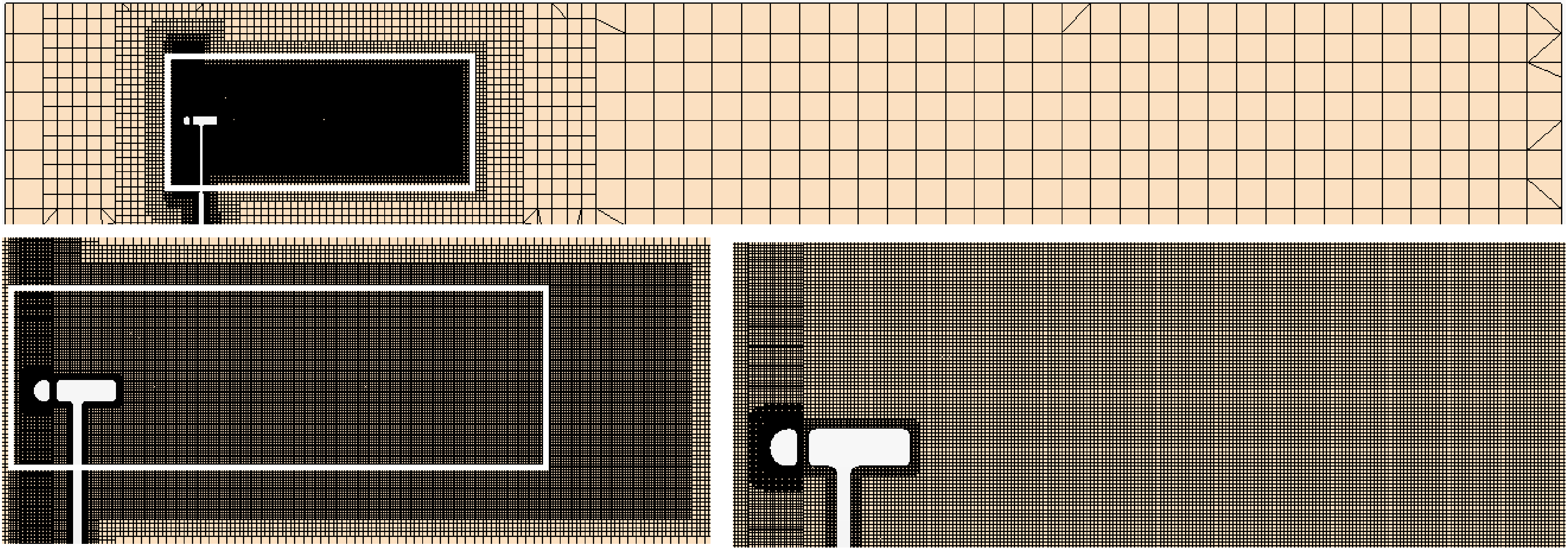
1. Four wind speeds: 5, 10, 15 and 25 m/s
2. Rotor angular velocity: 72 rpm
3. Turbulence intensity: 0.5%

Computational Domain and Boundary Conditions:





Grid:



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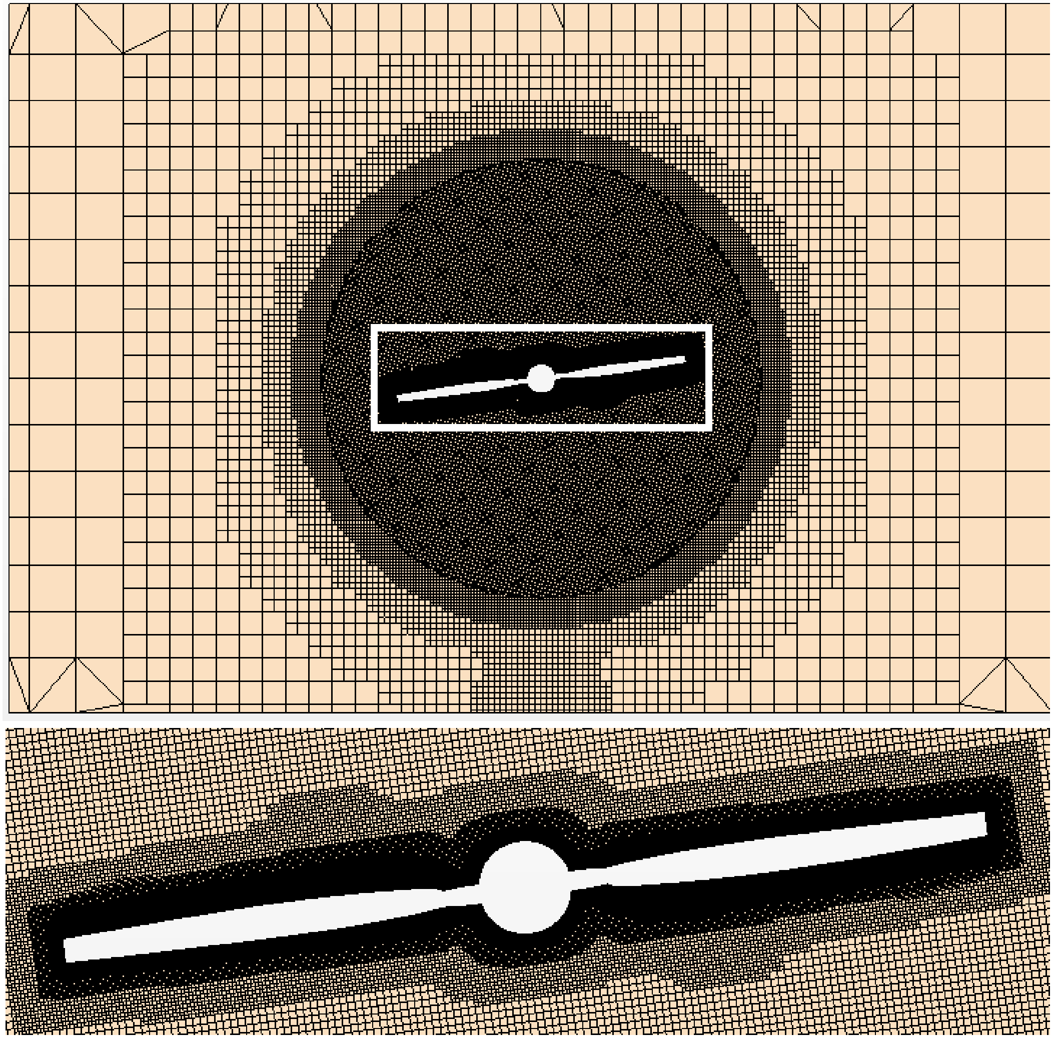
Grid:



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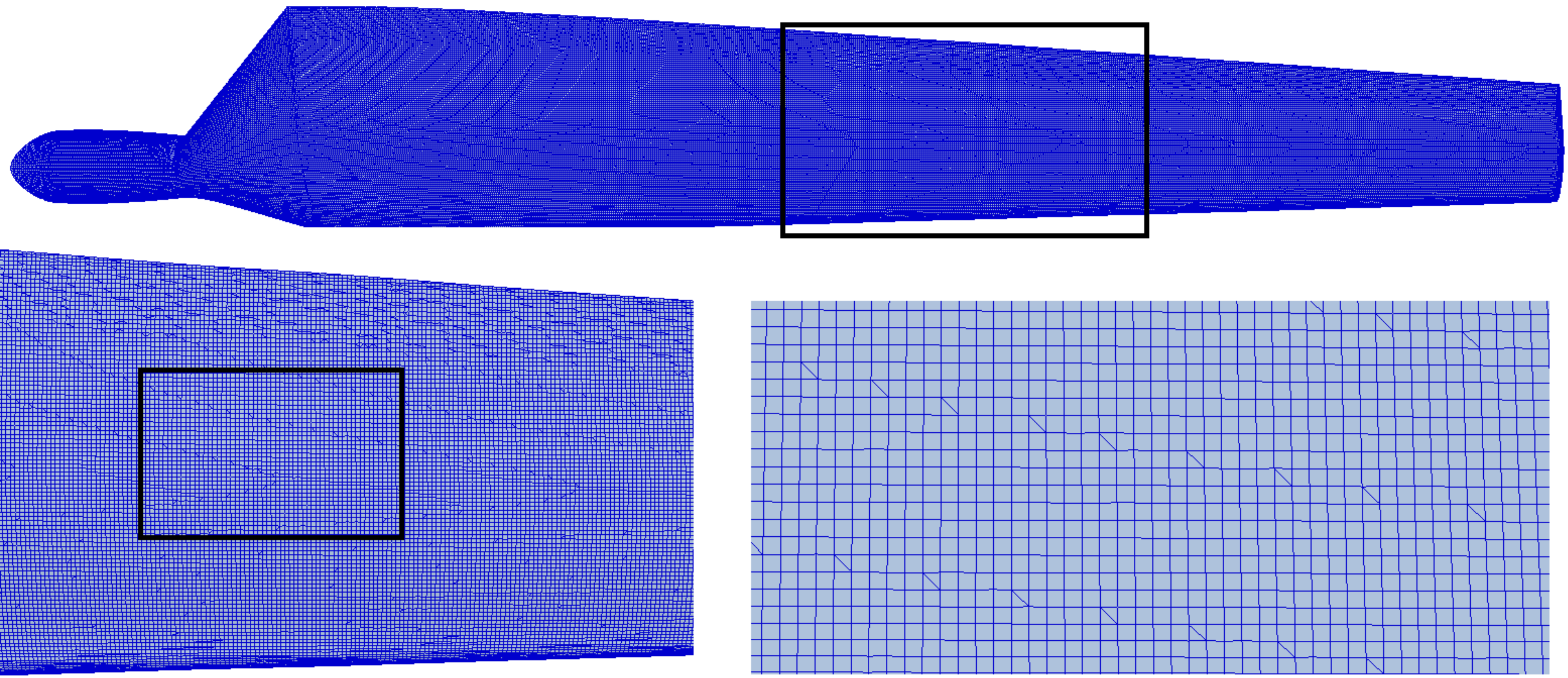

Grid convergence study:

Richardson (1911), Richards (1997), Stern et al. (2006), Mchale and Friedman (2009).

Grid convergence study:

Wind Speed: 25 m/s

Turbulence model: nonlinear quadratic SST k-w model

Grid convergence study:

Wind Speed: 25 m/s

Turbulence model: nonlinear quadratic SST k-w model

Grid	Grid Refinement	Time step (s)	# of cells
I	Fine	0.001155/1.2	26, 806, 032
II	Medium	0.001155	17, 345, 028
III	Coarse	0.001155 × 1.2	11, 362, 711

Grid convergence study:

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I	Fine	0.001155/1.2	26, 806, 032
II	Medium	0.001155	17, 345, 028
III	Coarse	0.001155×1.2	11, 362, 711

Grid	Power (W)	Thrust (N)
I	12574.13	3927.126
II	12108.03	3912.806
III	11150.63	3888.066

Grid convergence study: $R_G = \frac{S_I - S_{II}}{S_{II} - S_{III}}$, $U_G = 1.25\left|\frac{S_I - S_{II}}{S_{II}(r_{12}^p - 1)}\right|$.

Wind Speed: 25 m/s

Turbulence model: nonlinear quadratic SST k-w model

Grid	Grid Refinement	Time step (s)	# of cells
I	Fine	0.001155/1.2	26,806,032
II	Medium	0.001155	17,345,028
III	Coarse	0.001155 × 1.2	11,362,711

Grid	Power (W)	Thrust (N)
I	12574.13	3927.126
II	12108.03	3912.806
III	11150.63	3888.066

Quantity	R_G	p	$U_G \% S_{II}$
Power	0.49	4.99	4.52
Thrust	0.58	4.03	0.58

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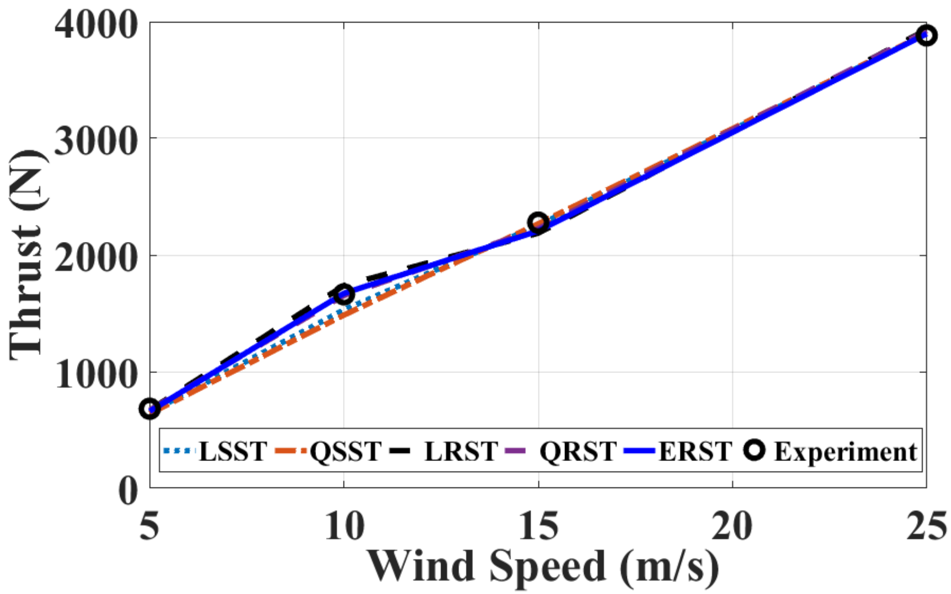
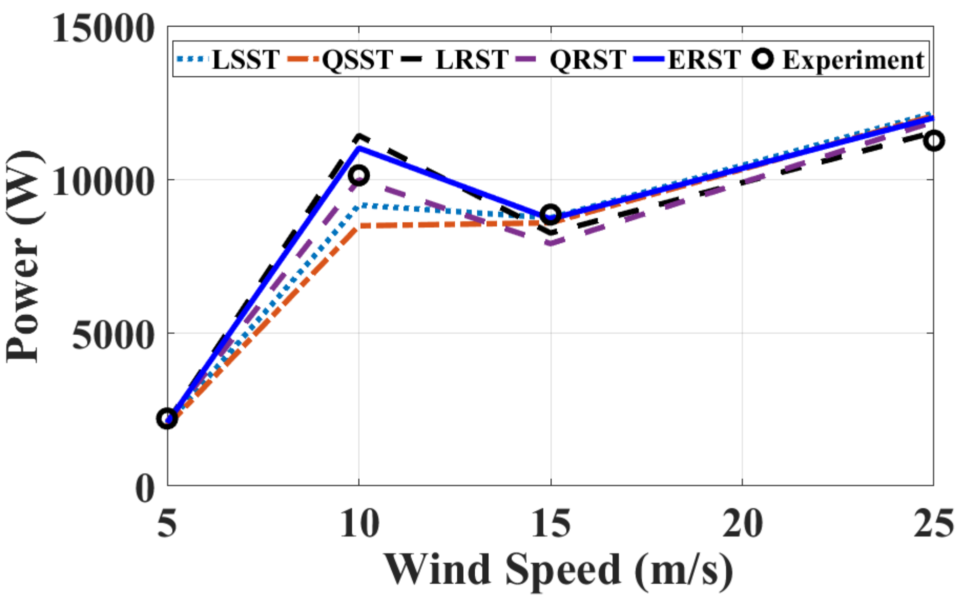
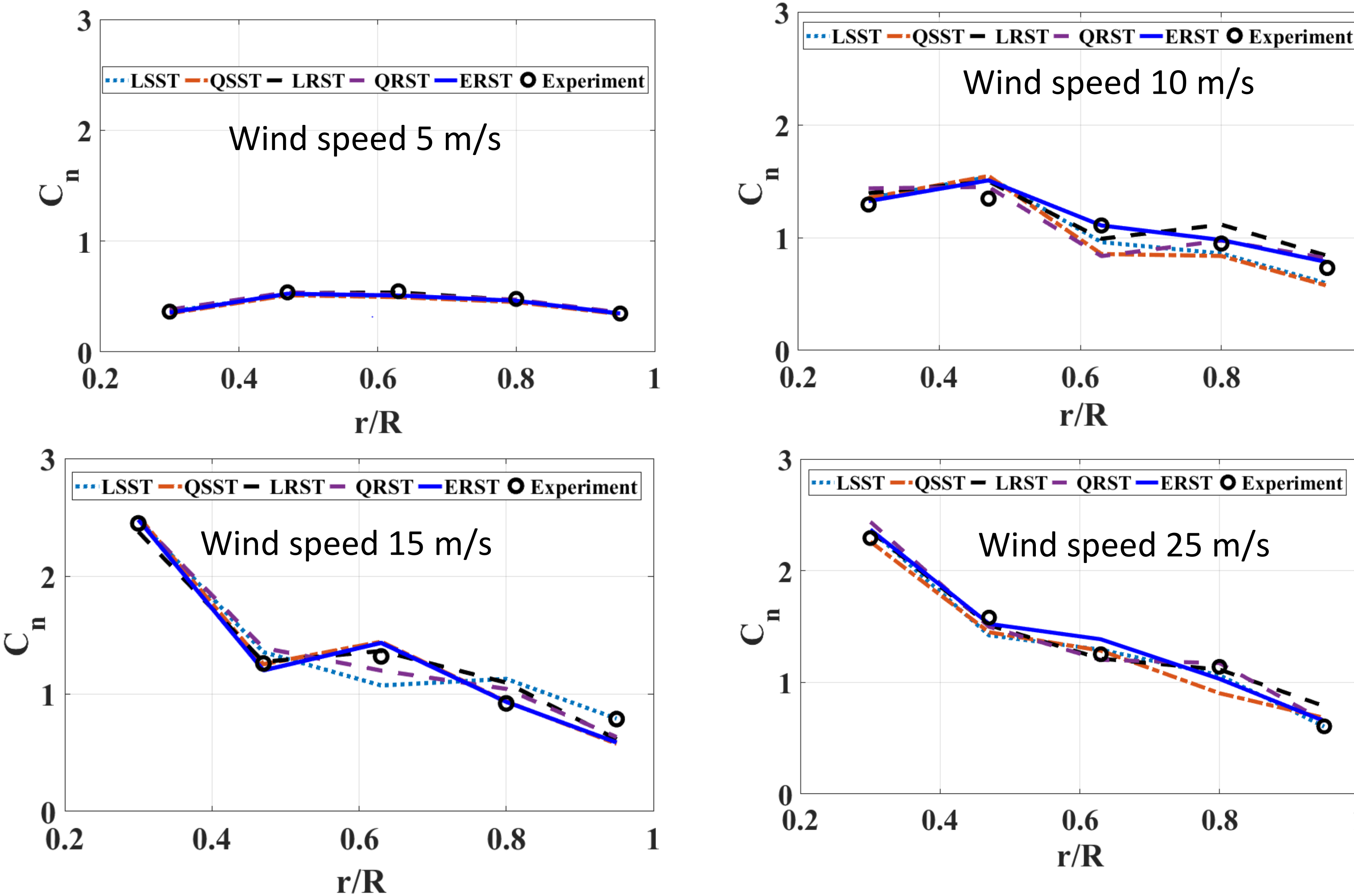
Thrust and Power



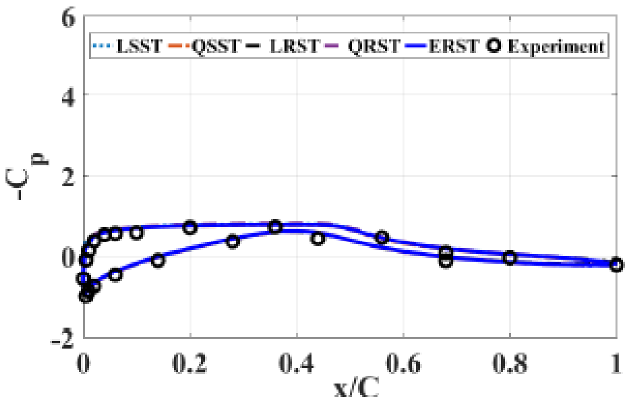


Radial distribution of normal force coefficient

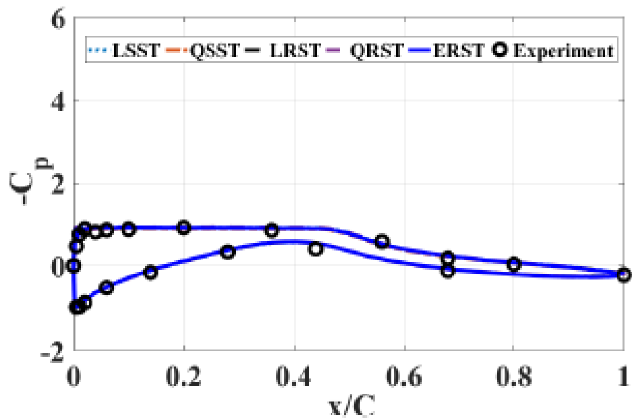


Chordwise pressure coefficient distribution

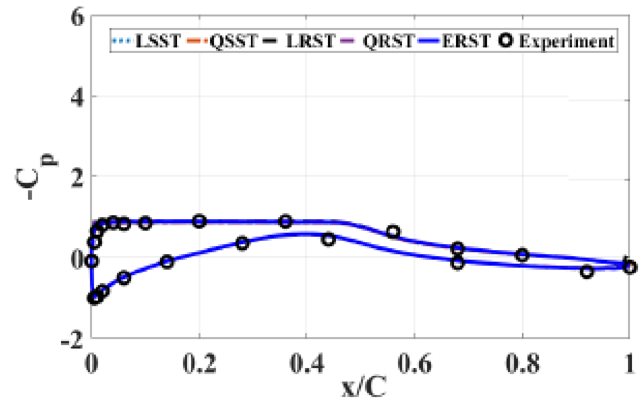
Wind speed 5 m/s



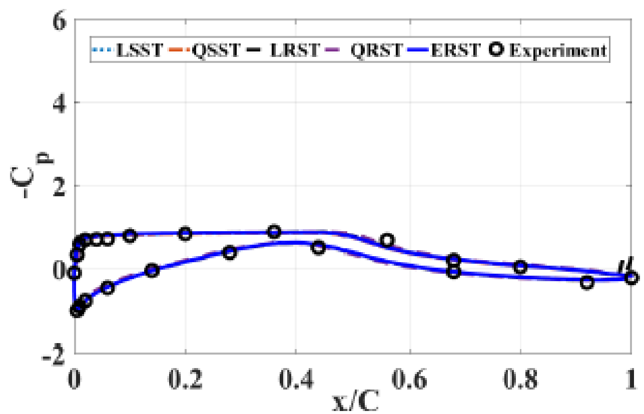
(a) $r/R = 0.30$



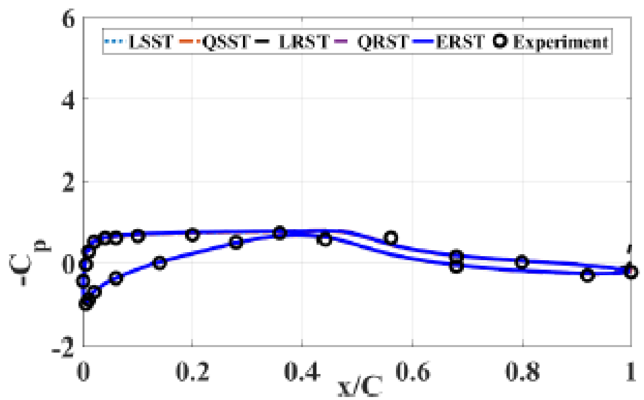
(b) $r/R = 0.47$



(c) $r/R = 0.63$



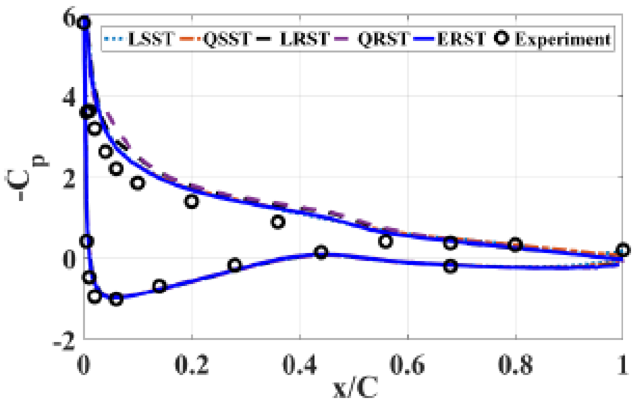
(d) $r/R = 0.80$



(e) $r/R = 0.95$

Chordwise pressure coefficient distribution

Wind speed 10 m/s



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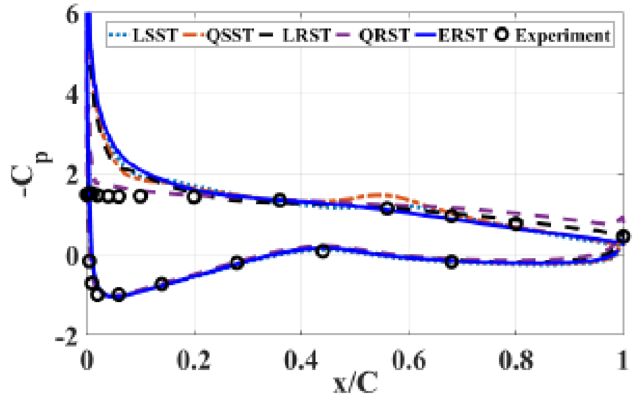
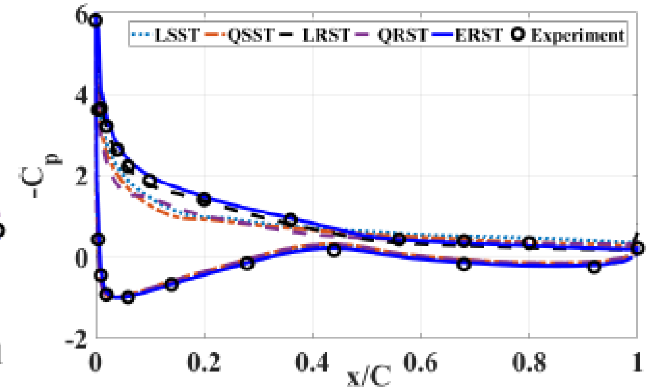


(b) $r/R = 0.47$



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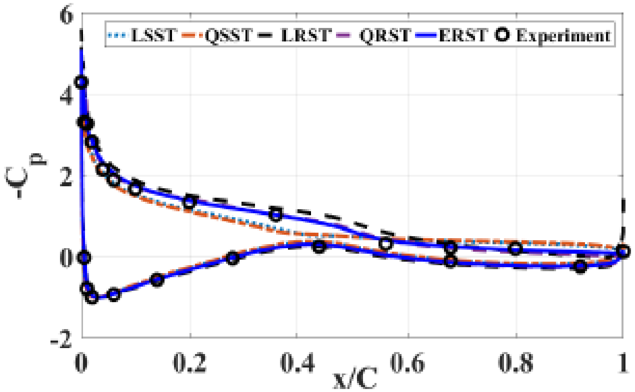
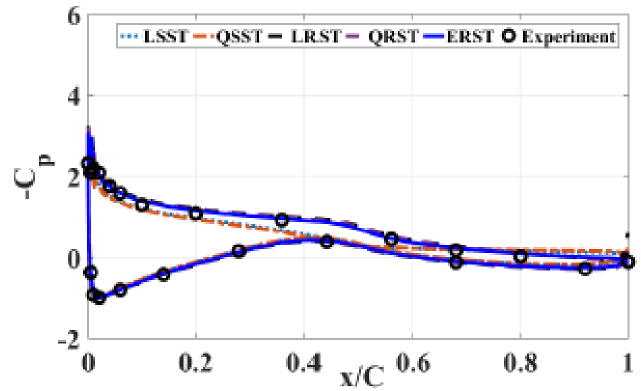


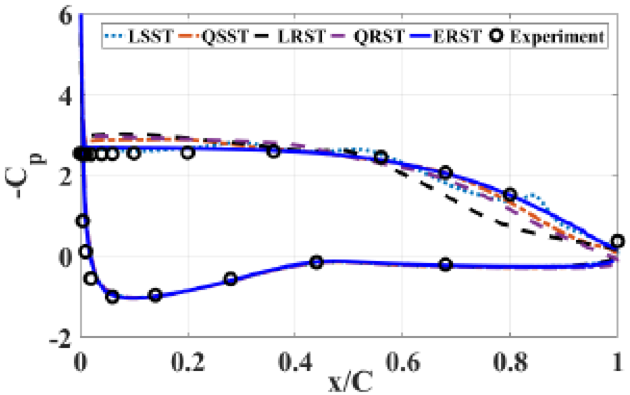
(d) $r/R = 0.80$



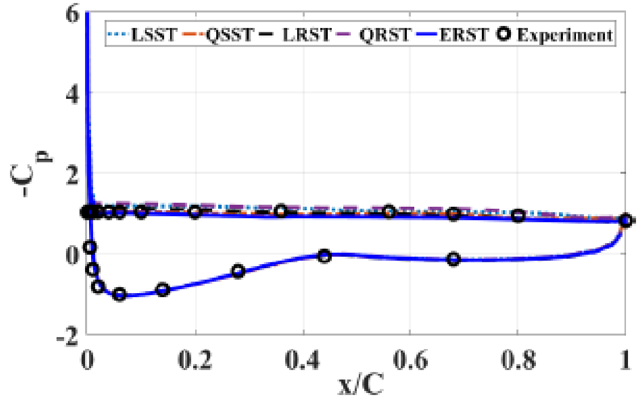
(e) $r/R = 0.95$

Chordwise pressure coefficient distribution

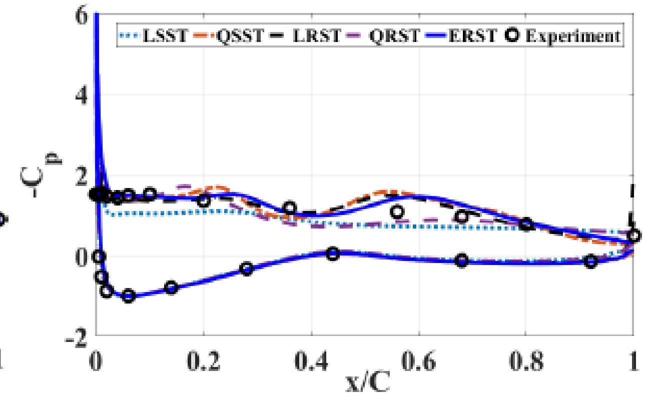
Wind speed 15 m/s



(a) $r/R = 0.30$



(b) $r/R = 0.47$



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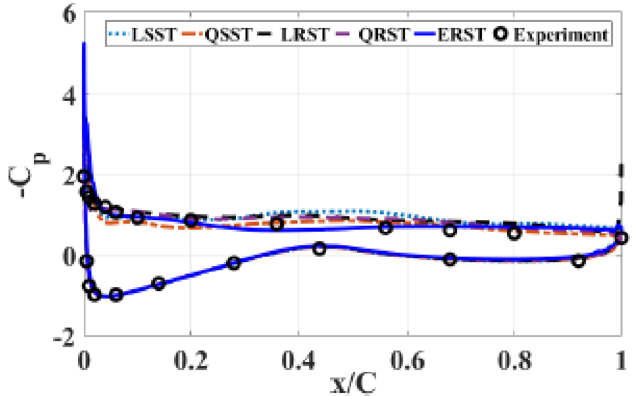

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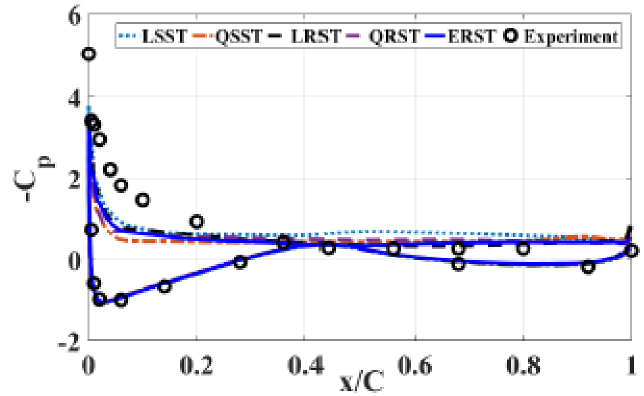
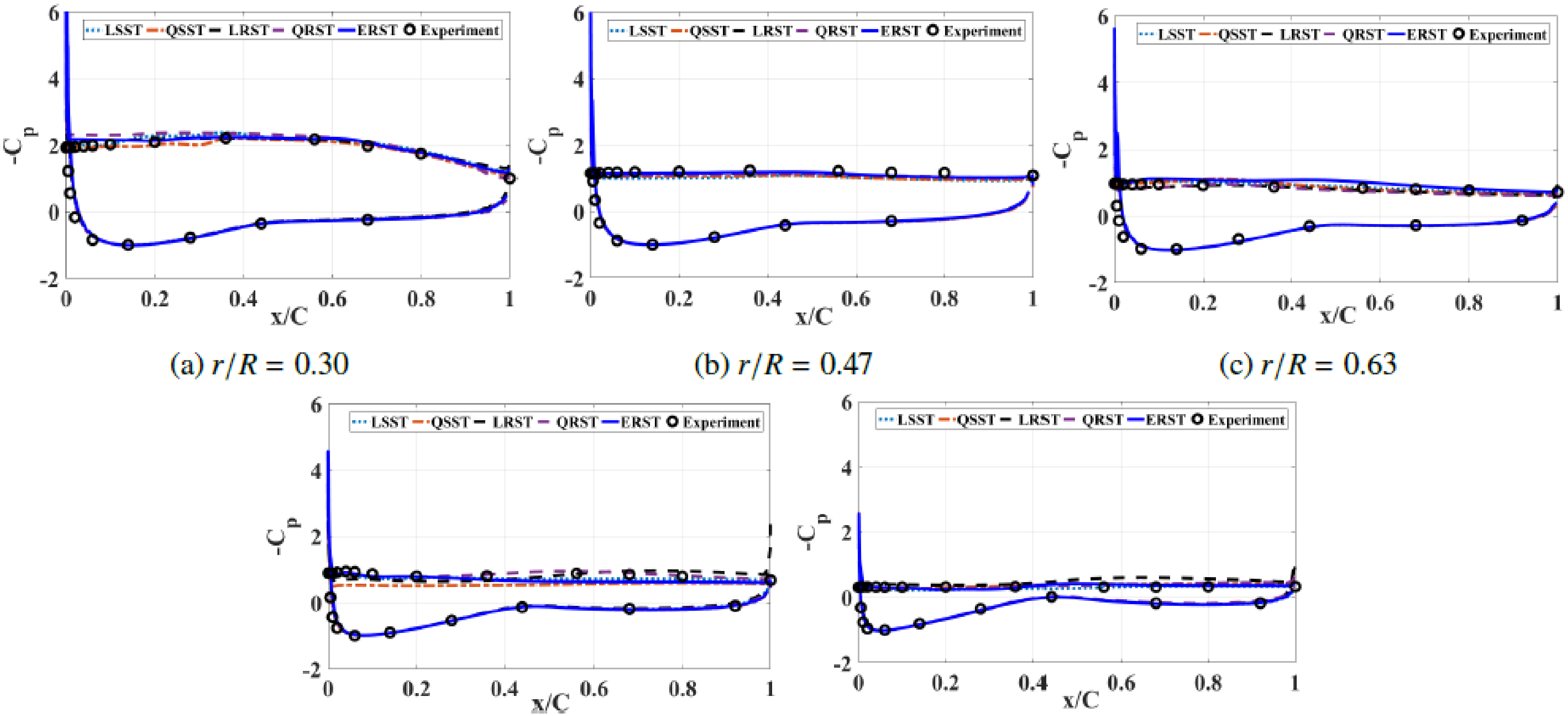


(e) $r/R = 0.95$

Chordwise pressure coefficient distribution

Wind speed 25 m/s



(a) $r/R = 0.30$

(b) $r/R = 0.47$

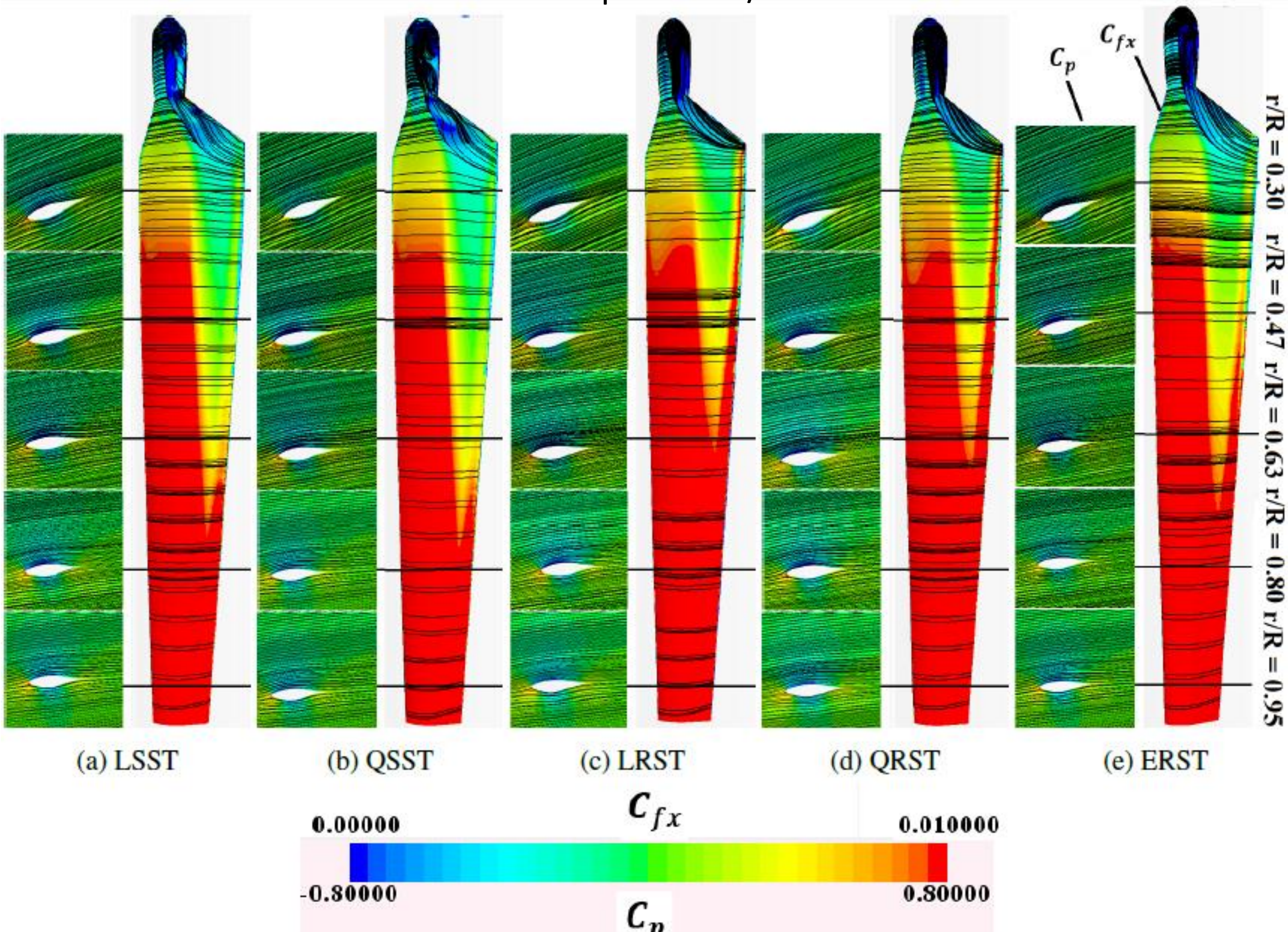
(c) $r/R = 0.63$

(d) $r/R = 0.80$

(e) $r/R = 0.95$

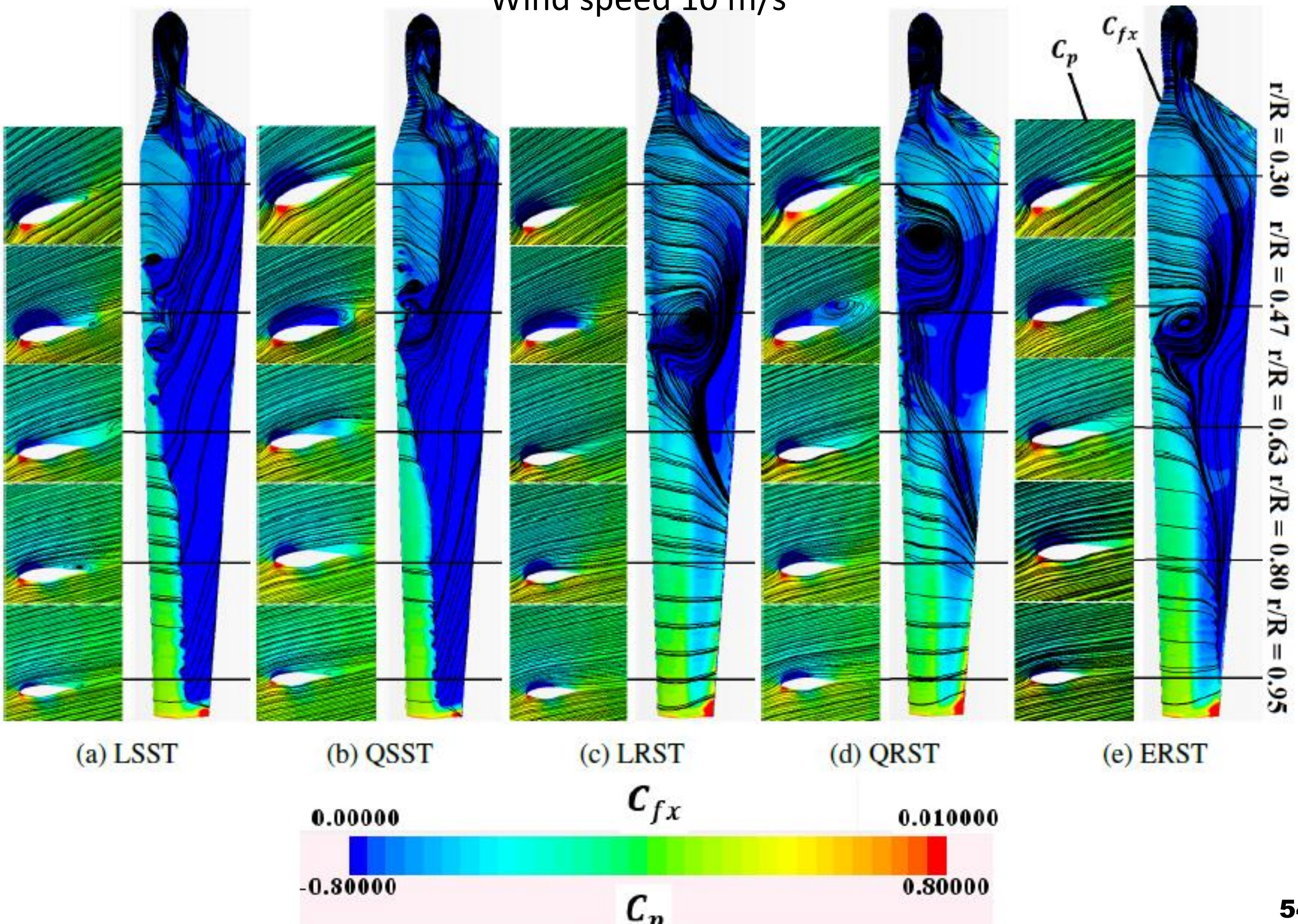
Flow visualization

Wind speed 5 m/s



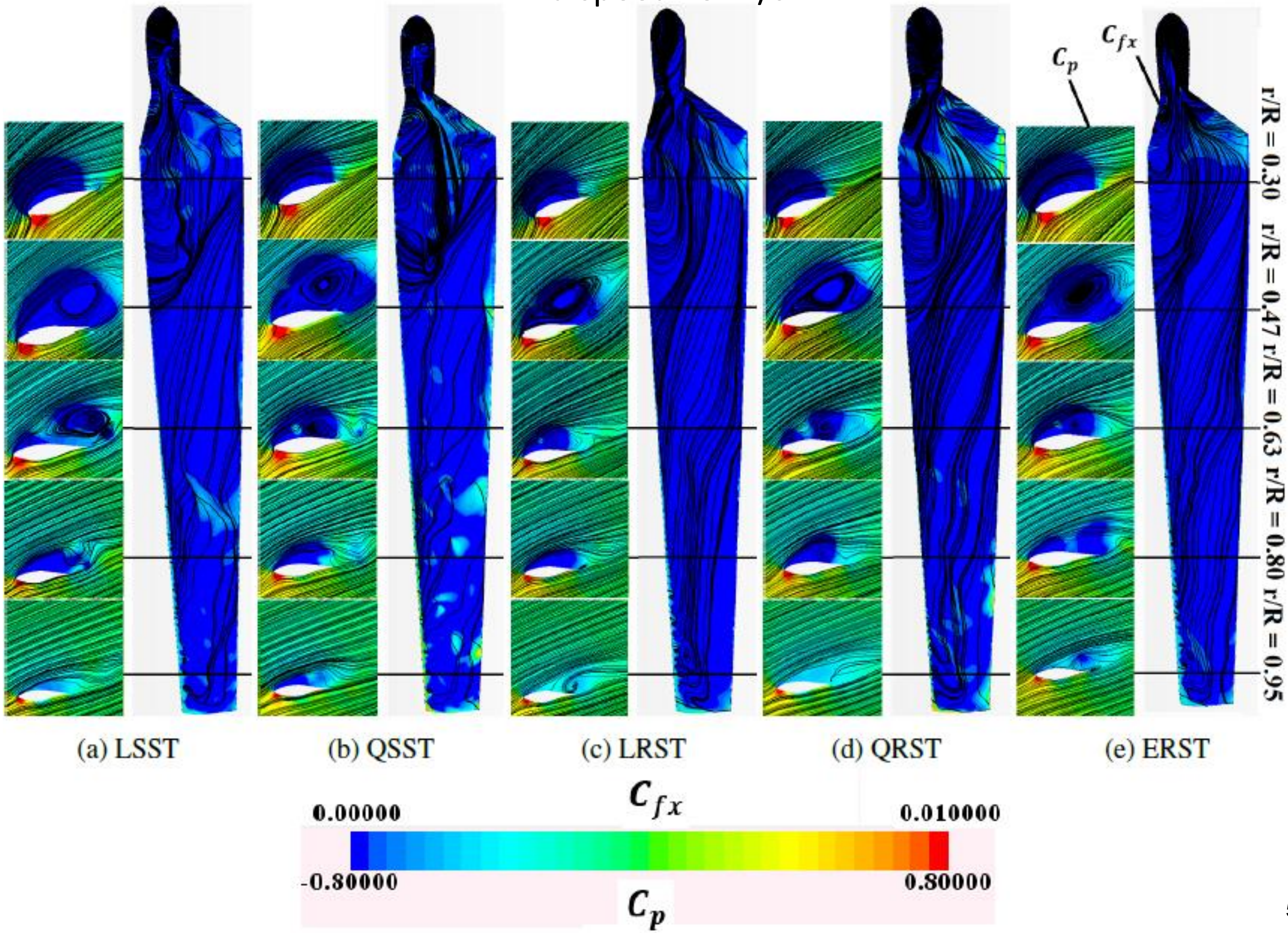
Flow visualization

Wind speed 10 m/s



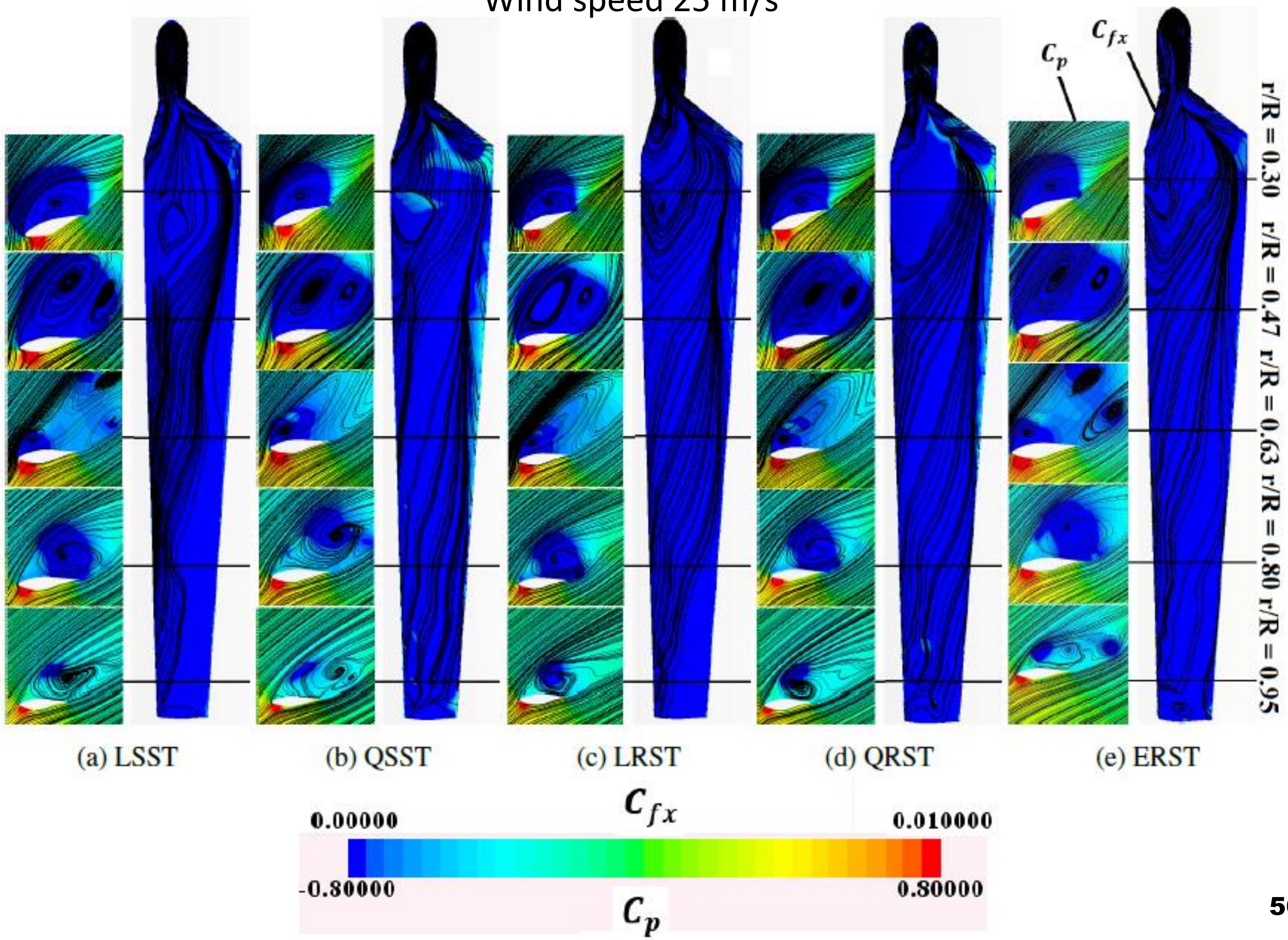
Flow visualization

Wind speed 15 m/s



Flow visualization

Wind speed 25 m/s



Evaluation of the turbulent flow anisotropy

Boussinesq hypothesis

$$\gamma_\tau = \mathrm{atan}\left\{\frac{\tau_{23}}{\tau_{12}}\right\}, \qquad \gamma_g = \mathrm{atan}\left\{\frac{\frac{\partial U_2}{\partial x_3} + \frac{\partial U_3}{\partial x_2}}{\frac{\partial U_1}{\partial x_2} + \frac{\partial U_2}{\partial x_1}}\right\},$$

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$$\left|\gamma_g - \gamma_\tau\right|$$

Evaluation of the turbulent flow anisotropy

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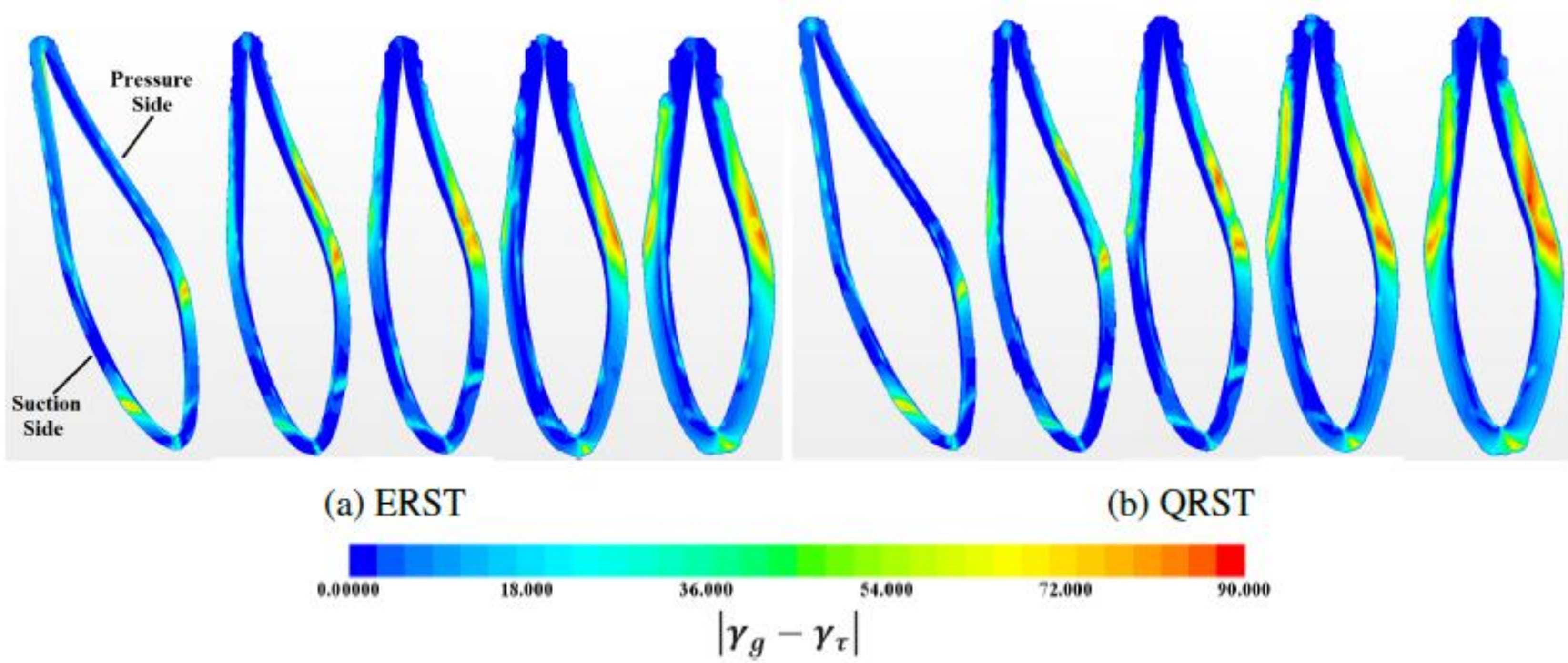
$$\left|\gamma_g - \gamma_\tau\right|$$

This evaluation is restricted to the boundary layer region

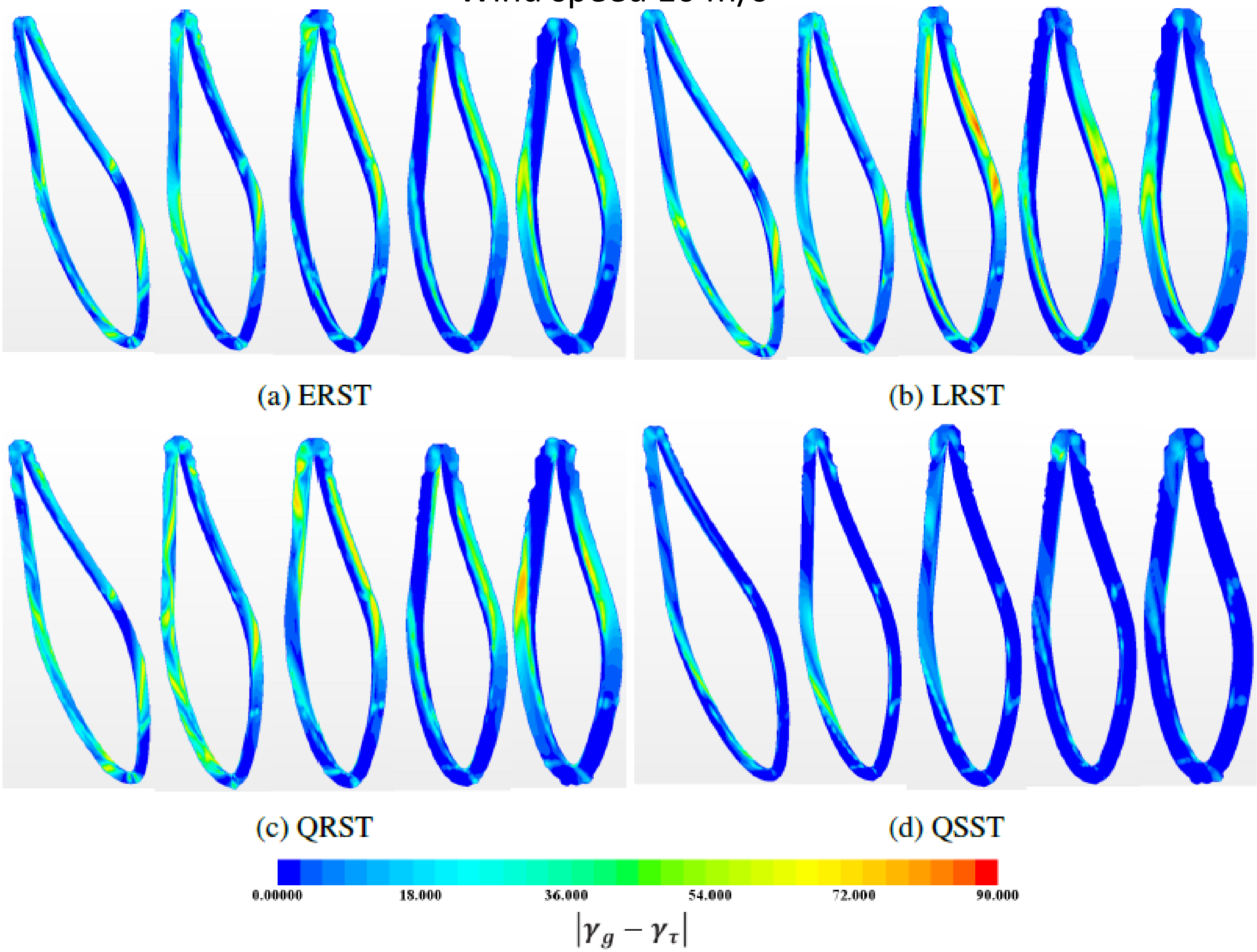
Evaluation of the turbulent flow anisotropy

Wind speed 5 m/s



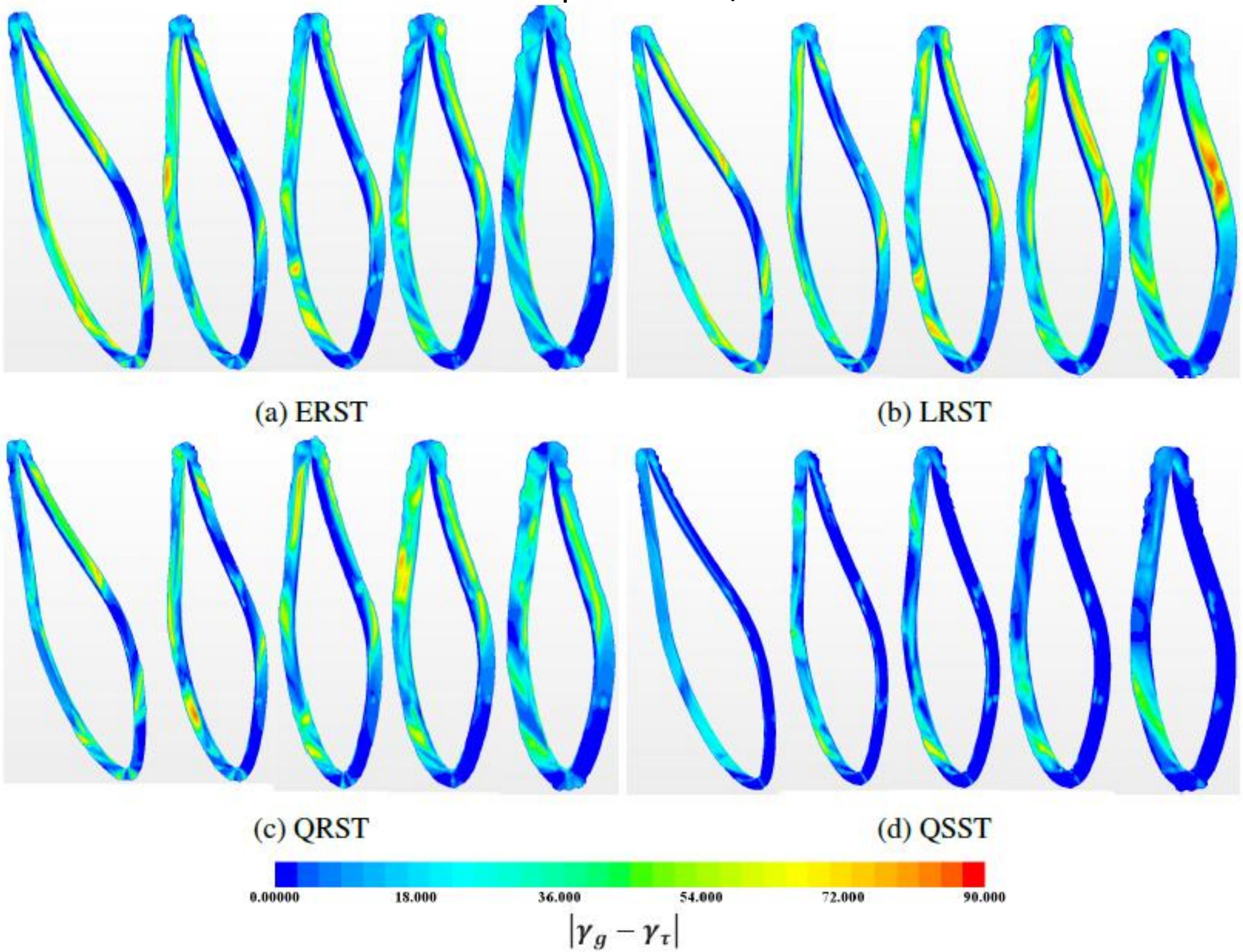
Evaluation of the turbulent flow anisotropy

Wind speed 10 m/s



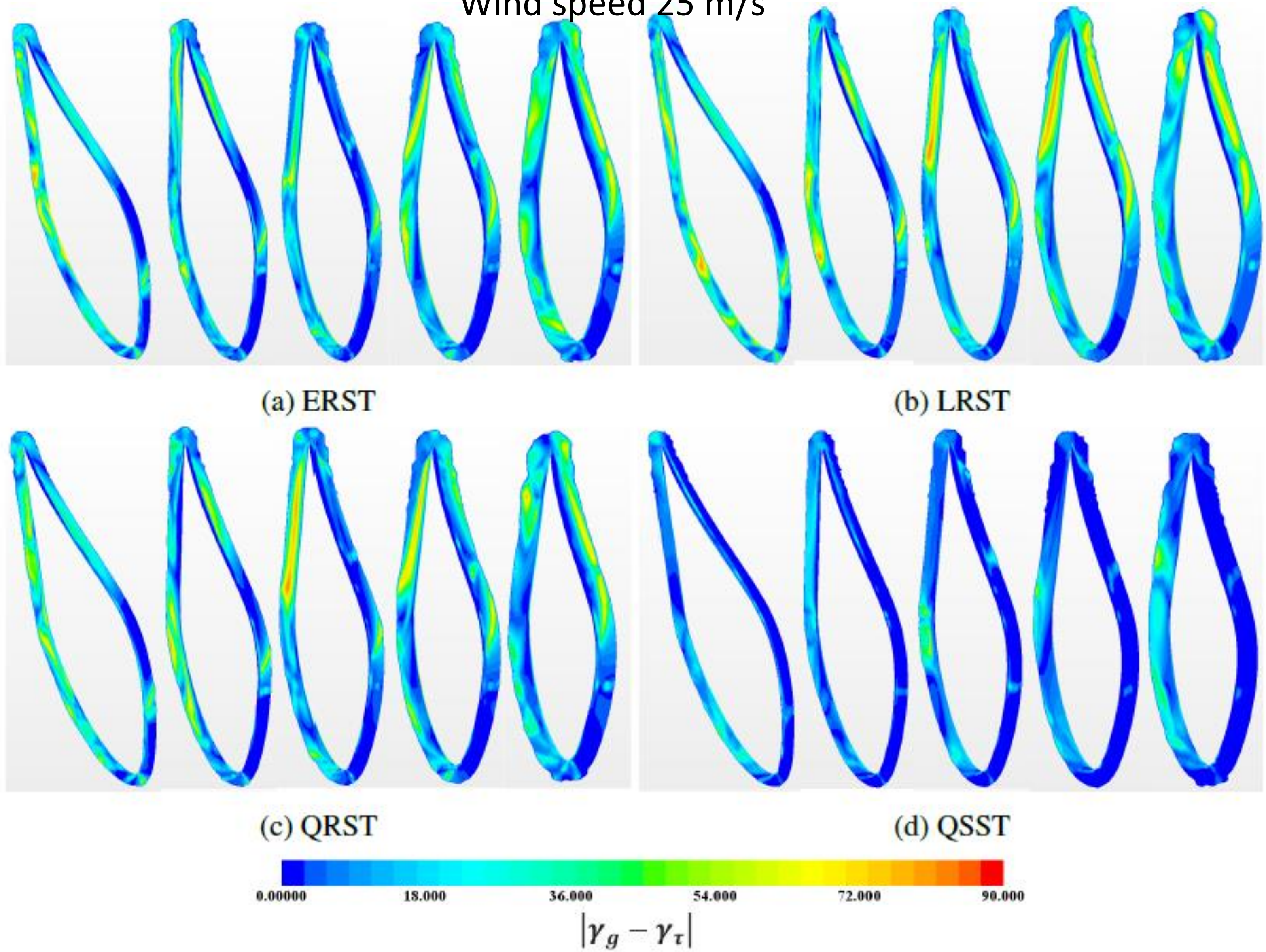
Evaluation of the turbulent flow anisotropy

Wind speed 15 m/s



Evaluation of the turbulent flow anisotropy

Wind speed 25 m/s



Time-dependent variables

Time-dependent variables

The pressure at blade trailing edge at r/R = 0.80

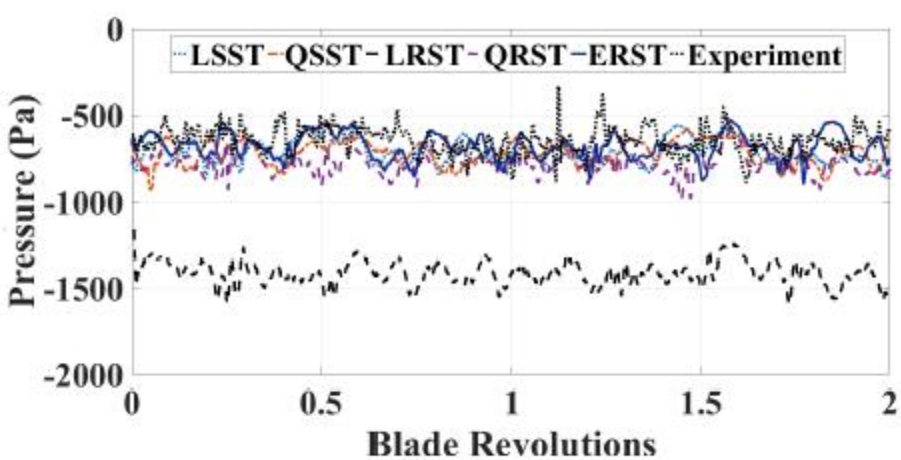
Time-dependent variables

The pressure at blade trailing edge at r/R = 0.80

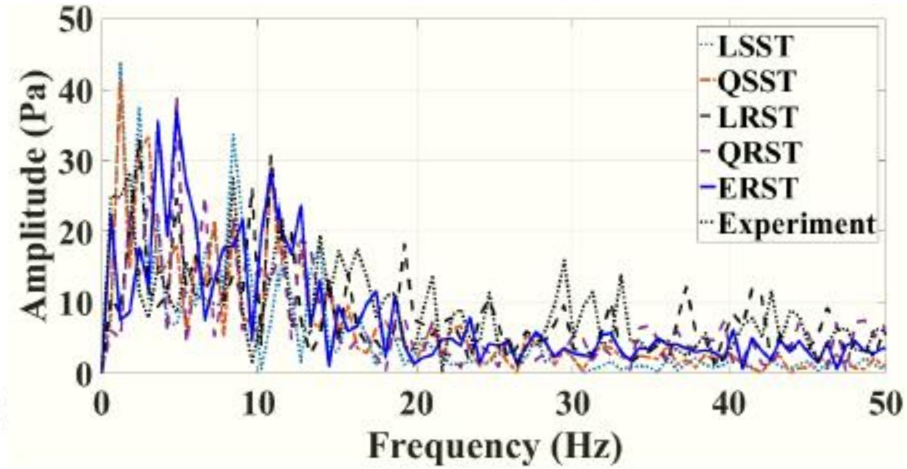
The thrust

Wind speed 25 m/s

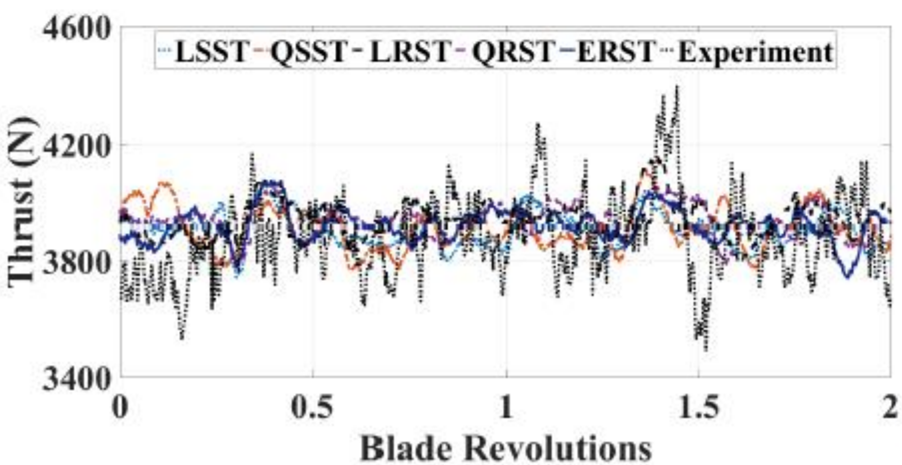
Time-dependent variables



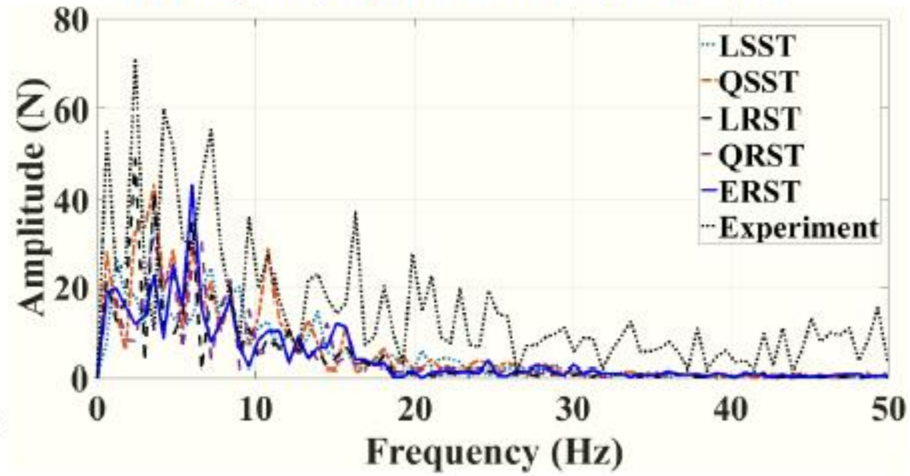
(e) Pressure evolution, wind speed 25 m/s



(f) Frequency spectrum, wind speed 25 m/s



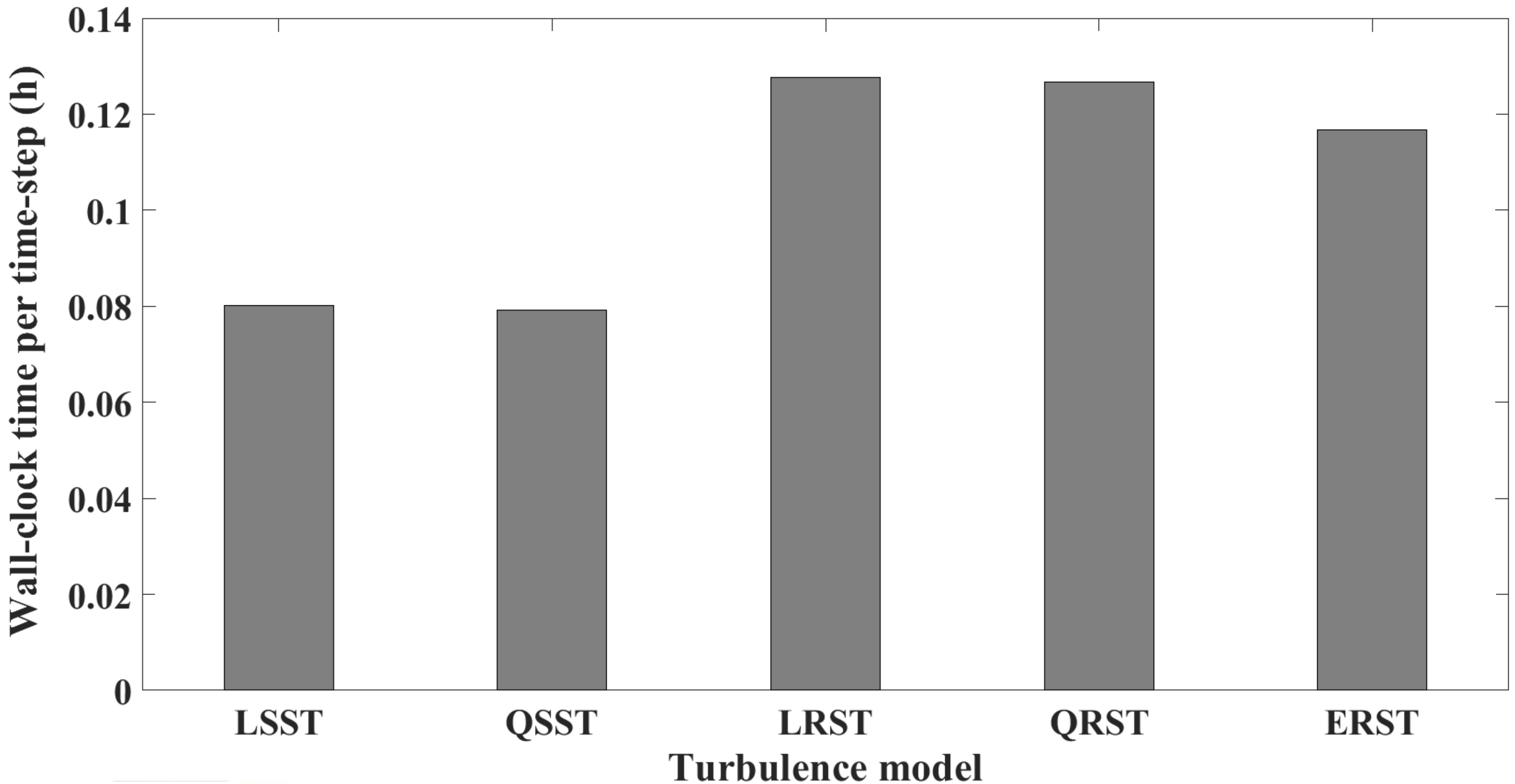
(g) Thrust evolution, wind speed 25 m/s



(h) Frequency spectrum, wind speed 25 m/s

Computational cost analysis

The computations are performed on a desktop computer consisting of 64-bit Intel Processors i9-9900KF@ 3.60GHz and 64 GB RAM.



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- The RST models, particularly the ERST and QRST, provide consistently more satisfactory predictions.

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- For the wind speed 10 m/s, the turbulence models return different predictions for the extent of the separated flow region over the suction side.

- An evaluation of the Boussinesq hypothesis implies that the turbulence models employing this assumption are inadequate for the prediction of wind turbines aerodynamics.

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- Regarding the thrust force, all the models underestimate the low-frequency fluctuations and also fail to predict the high-frequency fluctuations.

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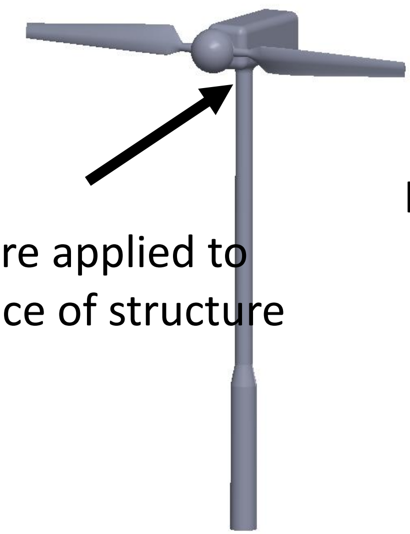
- All the models resolve satisfactorily the fluctuation spectrum of the pressure at a single point.
- Regarding the thrust force, all the models underestimate the low-frequency fluctuations and also fail to predict the high-frequency fluctuations.
- Finally, the ERST model appears to provide the best trade-off between the accuracy and the computational cost.

Future Work

- ❑ Fluid-structure interaction analysis

Abaqus

CFD



Loads are applied to the surface of structure

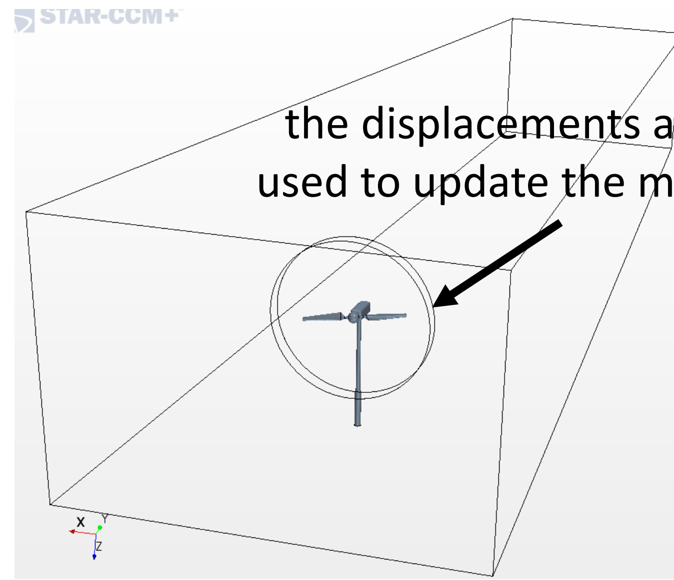
Data is exchanged at frequent intervals

pressure + wall shear stress

←

displacements

→



the displacements are used to update the mesh

Future Work

Simulações Aerodinâmicas

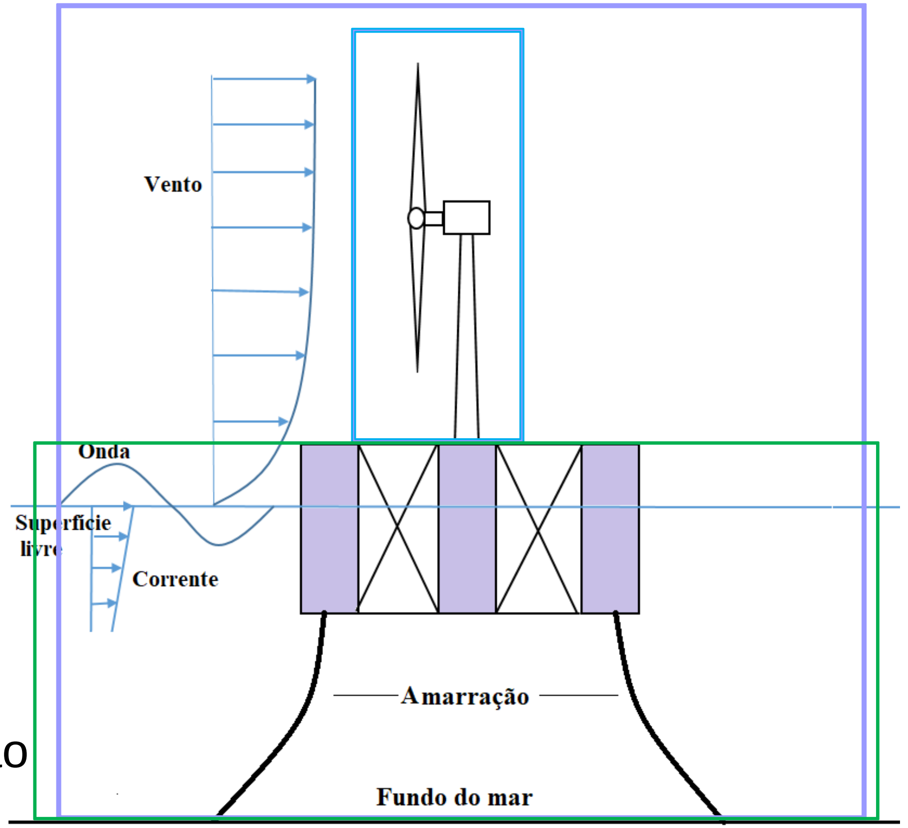
Turbina eólica

Simulações Hidrodinâmicas

semi-submersível + amarração

Simulações Hidro-aerodinâmicas

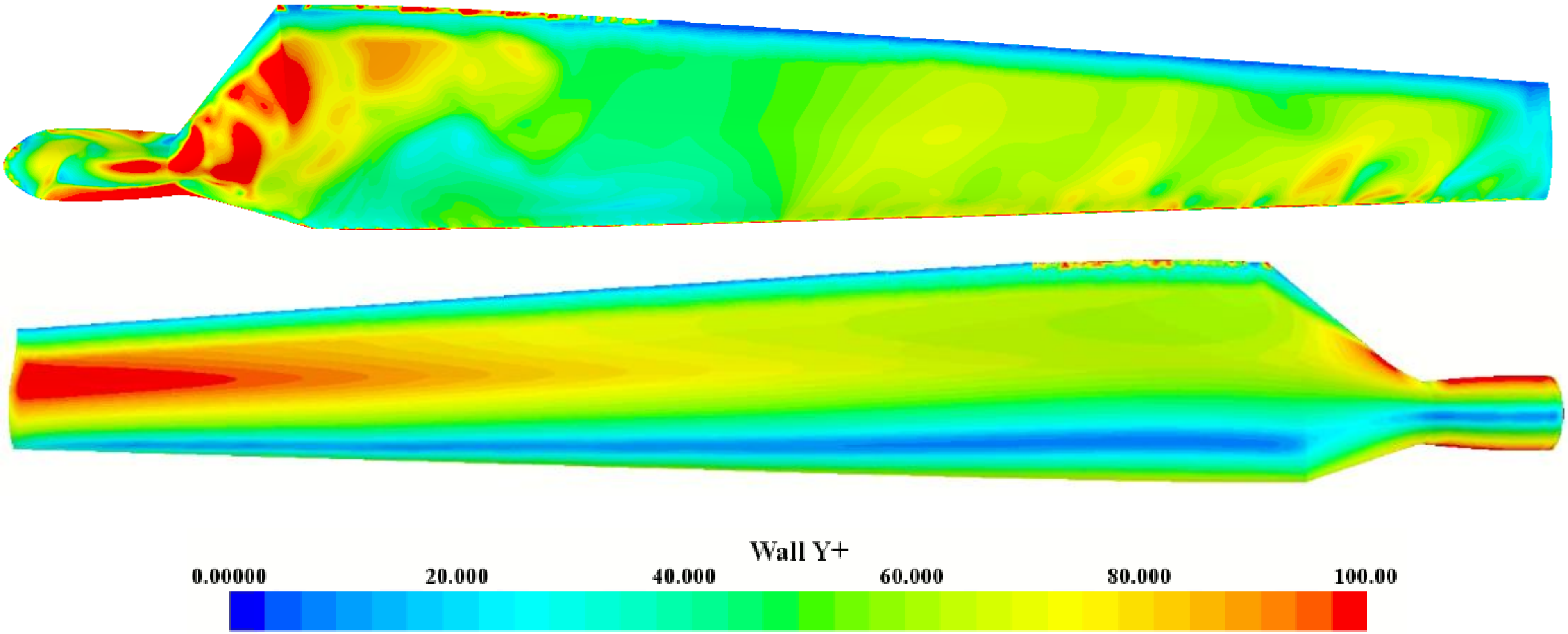
Turbina eólica + semi-submersível + amarração



Numero mínimo de células +
tamanho do passo de tempo +
um modelo de turbulência adequado (Modelos não lineares ou modelos de Reynolds)

Future Work

- Evaluation of the performance of the ERST and LRST models without using the wall function.



Contributions

❑ Submitted Publications

- Amiri M.M., Shadman M., Segen F. Estefen, URANS simulations of a horizontal axis wind turbine under stall condition using Reynolds stress turbulence models, Energy, 2020.

Questions?