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Validation of high-fidelity CFD solutions for the analysis of aerodynamic loads on wind turbines

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SINTEF Ocean | Ships and Ocean Structures | Marine CFD

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Motivations and background

Current trends

- Offshore wind production moves further to exposed ocean areas
- Size of turbines and power output increase
- Large parks of turbines are deployed to harvest wind energy both onshore and offshore

Challenges for contemporary simulation tools regarding rotor aerodynamics

- prediction of integral and local loads on the individual rotor blades, which can be heavily unbalanced (*varying wind field, influence of the wake from a neighbour turbine, wave-induced motions together with the floater*);
- modelling of the dynamic behaviour of rotor vortex wake and resolution of far-field wake structures (*turbine-turbine interaction and noise radiated by the turbine*);
- interaction mechanisms between the rotor and anisotropic turbulent field of Atmospheric Boundary Layer (ABL).

Solution

- ✓ High-fidelity **Computational Fluid Dynamics (CFD)**: realistic media model, realistic structure model, realistic scale
- ✓ Accurate geometrical representation of the turbine (rotor, nacelle, tower)
- ✓ Adequate modelling of the turbulence field

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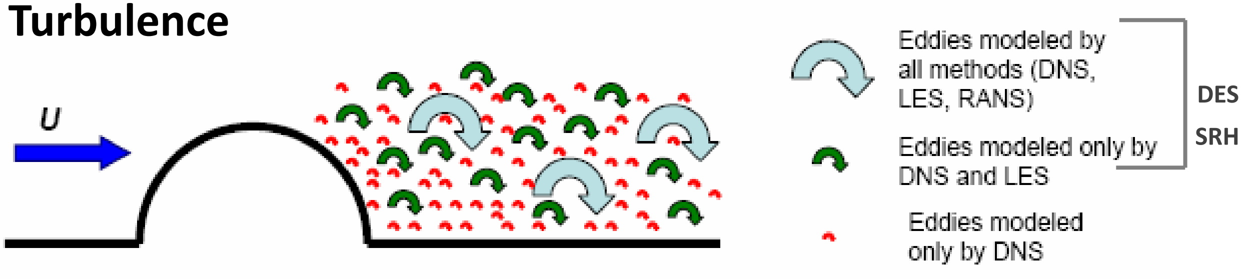
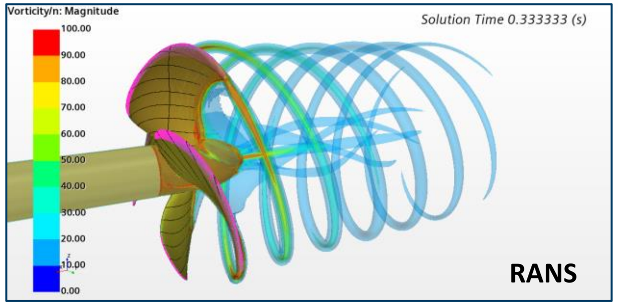
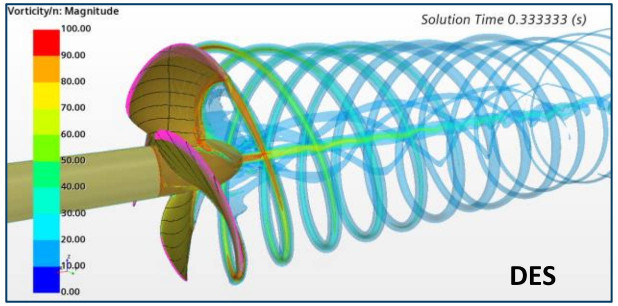
Choice of simulation strategies | (1)

Turbulence

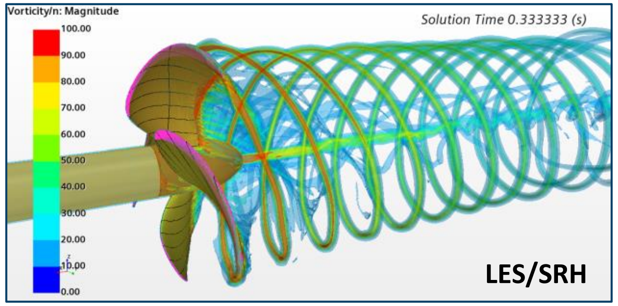




- **RANS** solves completely time-averaged and ensemble-averaged equations

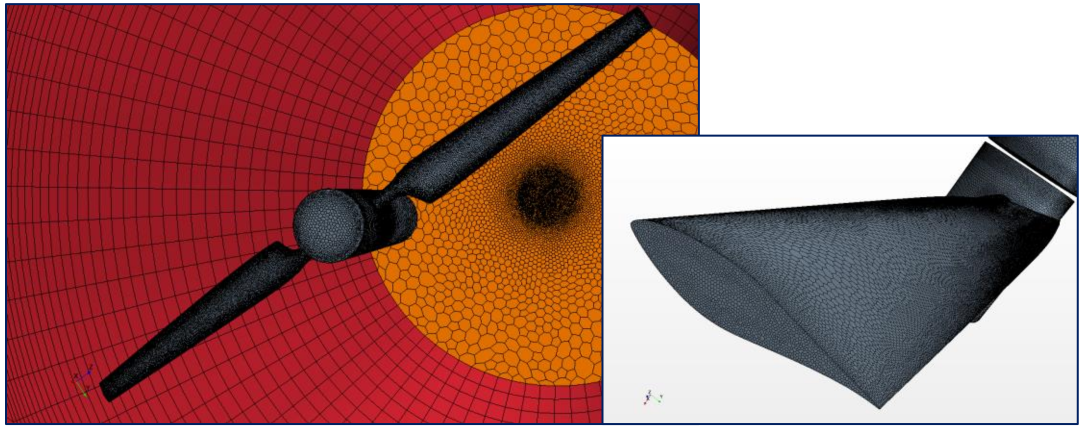


- **DES / SRH** couple RANS and LES solutions in a zonal or continuous manner, respectively



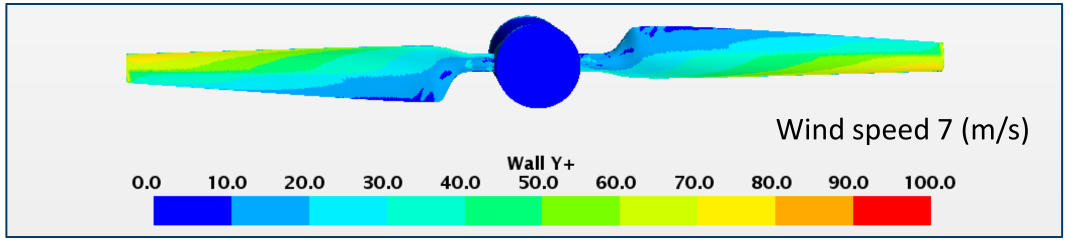
- **LES** solves partially averaged (filtered) equations

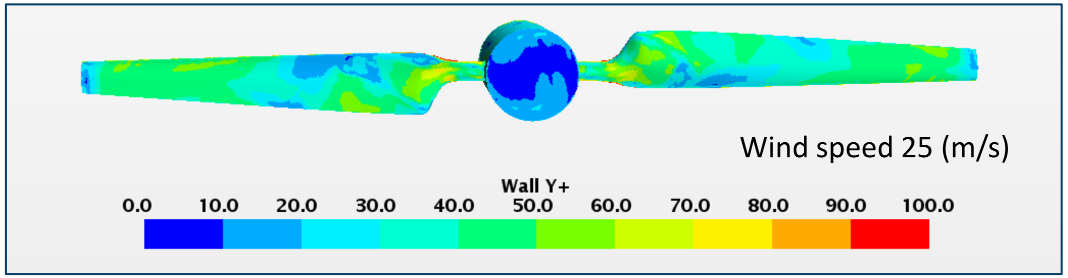
Geometry



✓ Fully resolved rotor

Near-wall treatment





✓ High-Re (Wall functions)

✓ All Y+ Treatment

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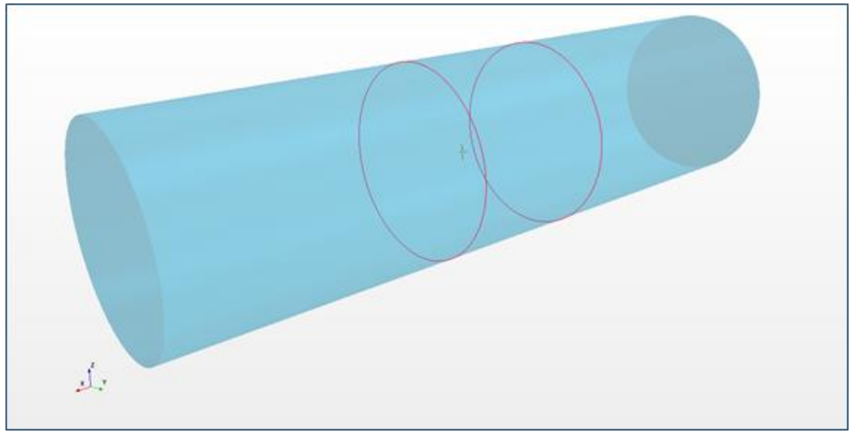
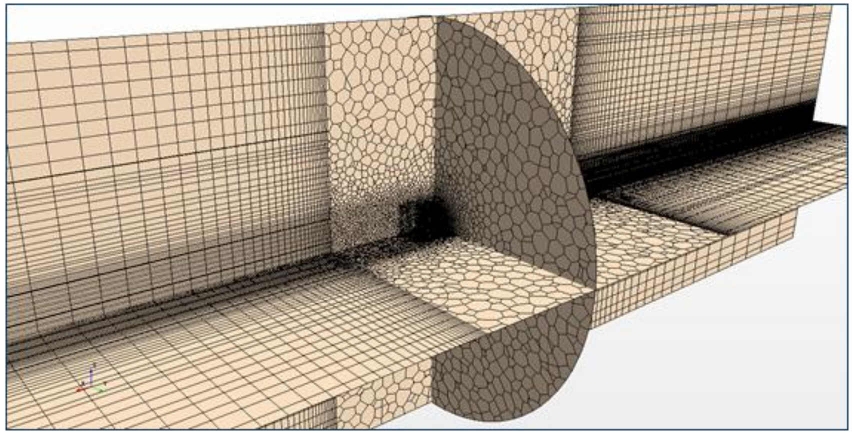
Choice of simulation strategies | (2)

Motions

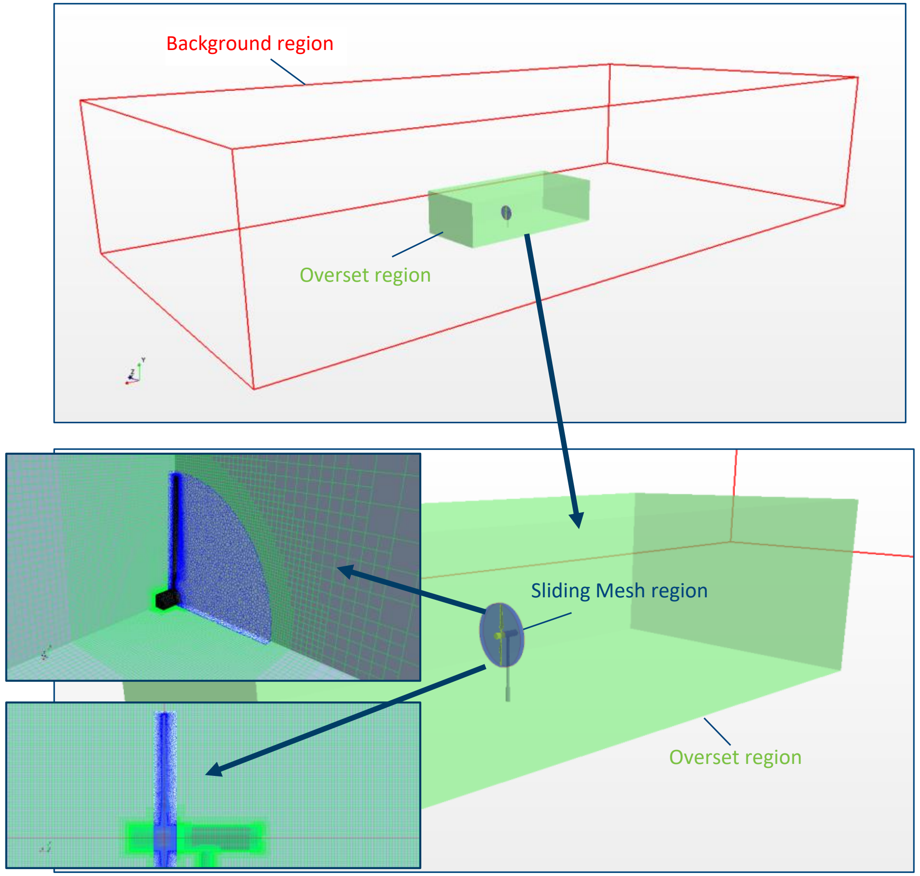
Straight, uniform flow template





- ✓ Moving Reference Frame (MRF)
- ✓ Steady or Unsteady
- ✓ One blade passage or complete domain

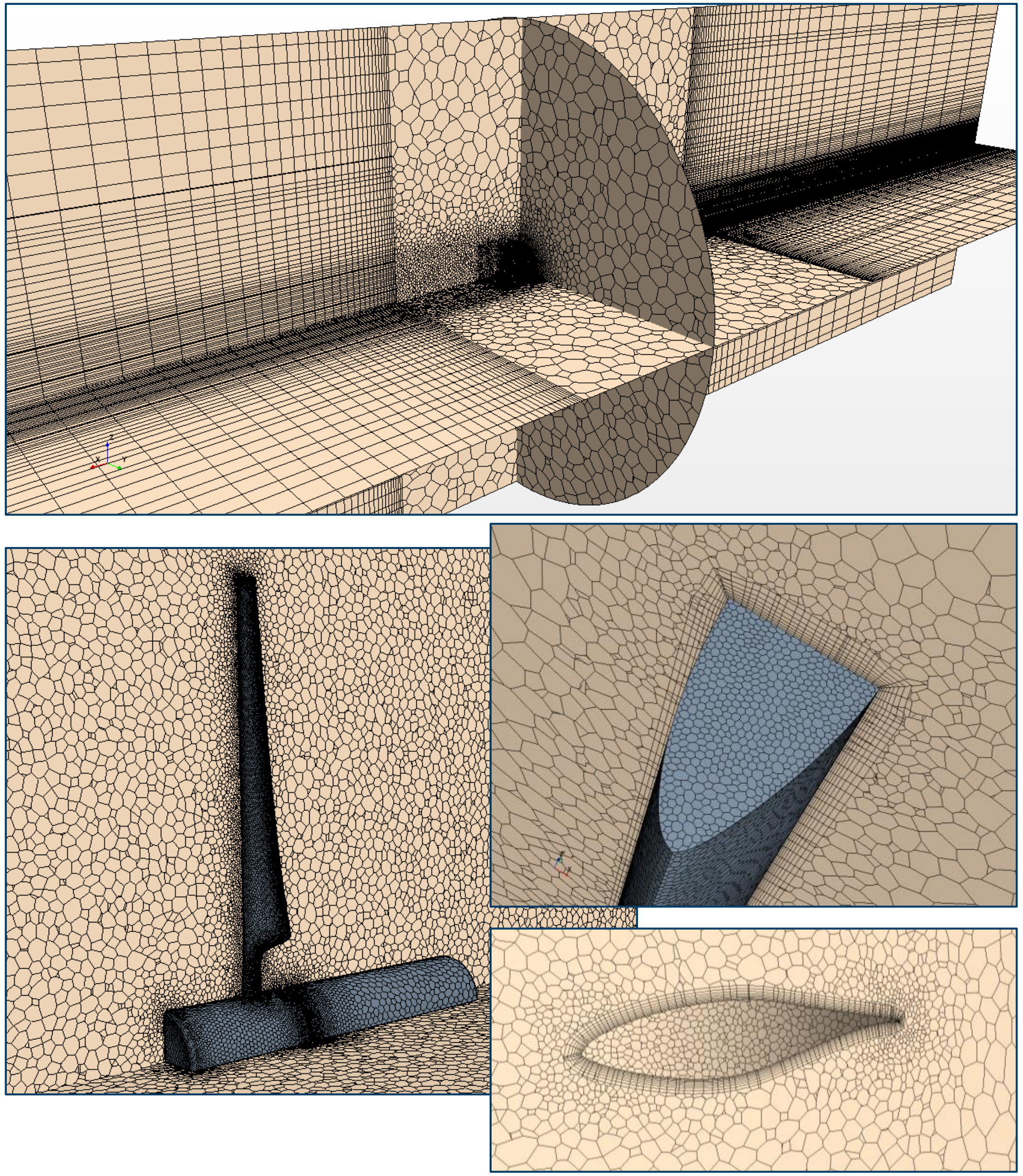
Generic 6DOF template



- ✓ Supports arbitrary motions
- ✓ Arbitrary wind direction
- ✓ Unsteady
- ✓ Allows inclusion of free surface

Details of numerical setup

Base mesh: Mesh 2 Y+30



Domain size: Xin×Xout×R = 18D×20D×5D

Mesh type:
- Polyhedral with prismatic extrusions (Straight flow setup)
- Polyhedral/Hex Trimmer (6DOF setup)

Target Y+: 30

Prism layers: 8 layers, total thickness 0.0015D, stretch factor 1.2

Total cell count:
- 6.7 mill (Straight flow setup)
- 8.2 mill (6DOF setup)

Solver: Segregated solver, incompressible

Time: Implicit unsteady, 1st order discretization

Flow regime: Fully turbulent

Rotor surface conditions: Hydrodynamically smooth

CFD software: STAR-CCM+ 2020.3 (15.06)

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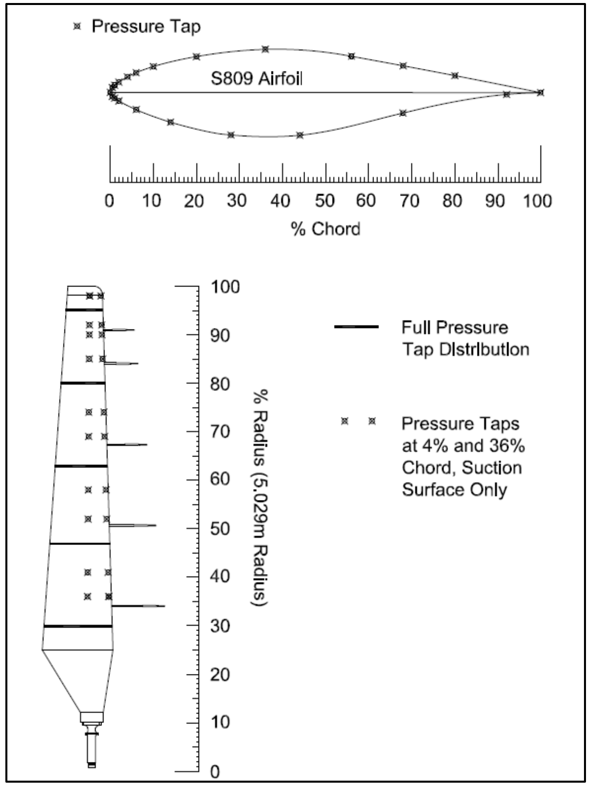
Test case of the UAE reference wind turbine

Rotor diameter [m]	10.058
Rotor swept area [m^2]	79.45352029
Collective pitch angle [deg]	3
Hub adaptor radius, rh [m]	0.508
Hub height [m]	0.79
Hub width [m]	0.91
Rotor shaft above Tower top [m]	1.034
Tower height above tunnel floor [m]	11.14

NREL Test ID	Wind speed	J=V/(nD)	TSR=pi/J
	(m/s)	(-)	(-)
s0700000	7	0.579970	5.416824
s1000000	10.1	0.836813	3.754234
s1300000	13.1	1.085372	2.894486
s1500000	15.1	1.251077	2.511110
s2000000	20.1	1.665341	1.886456
s2500001	25.1	2.079605	1.510668

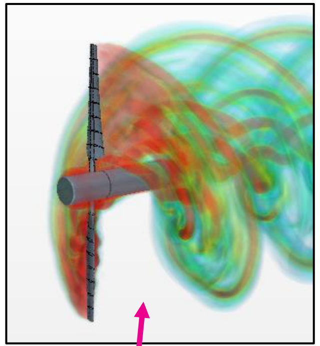
Average Air density (kg/m^3)	1.225
Average Air dynamic viscosity (Pa-s)	0.000017972
Yaw angle (deg)	0
Average Rotor rotational speed (RPM)	72



Focus of the present study

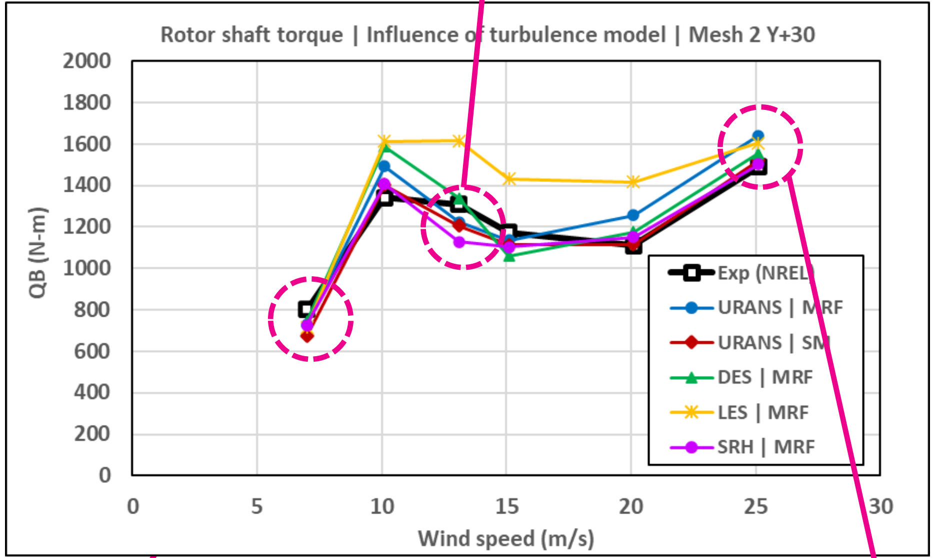
- Integral loads (Rotor shaft torque and Blade root flap bending moment)
- Pressure distribution along the blade sections
- Resolution of rotor wake field (w/o comparison with experimental data)

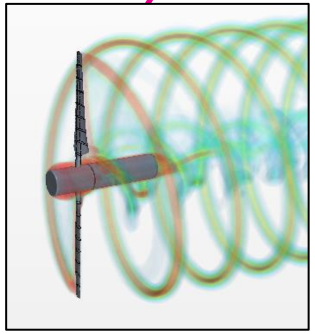
Results regarding different turbulence models | Integral loads



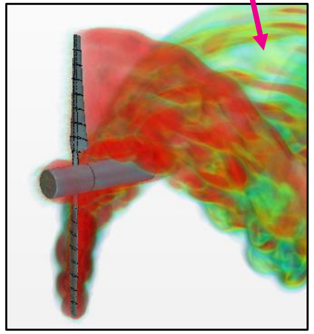
Vorticity magnitude, curl(U)/n

MRF – Straight flow setup using Moving Reference Frame
SM – 6DOF setup using Overset Mesh and Sliding Mesh

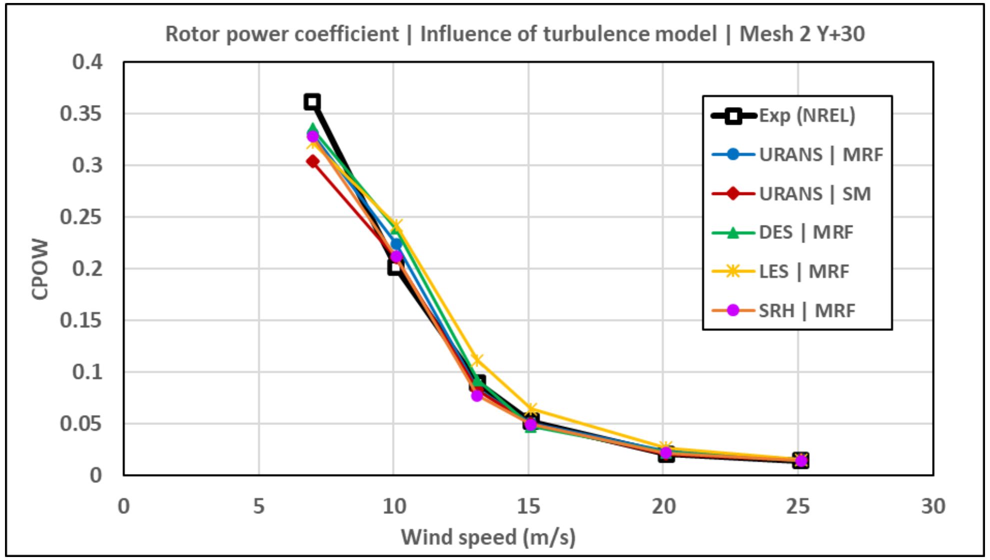


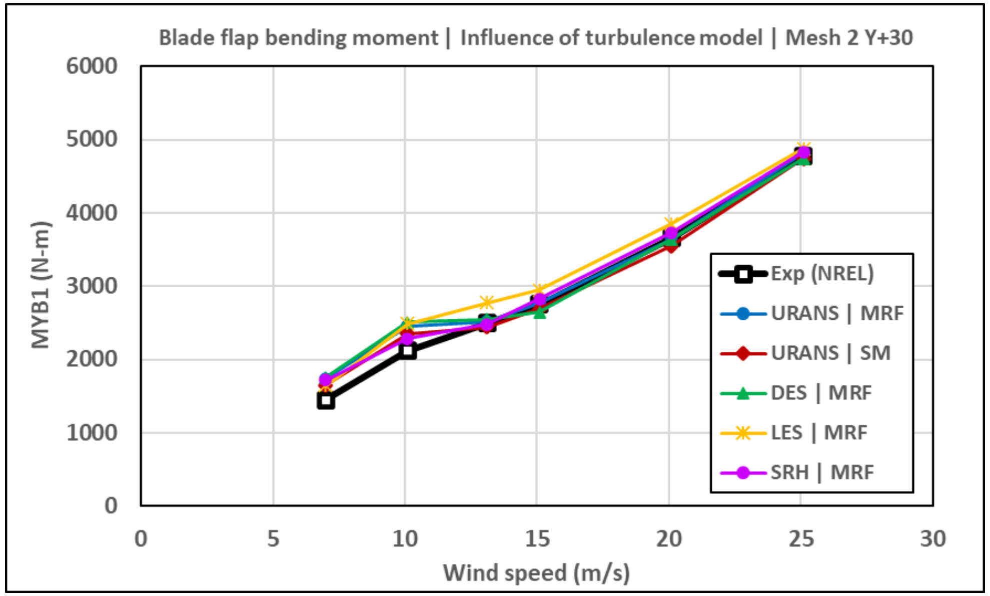


Vorticity magnitude, curl(U)/n



Vorticity magnitude, curl(U)/n





(!) Note:
Integral loads are given as time-averaged values over the last simulated revolution of the rotor

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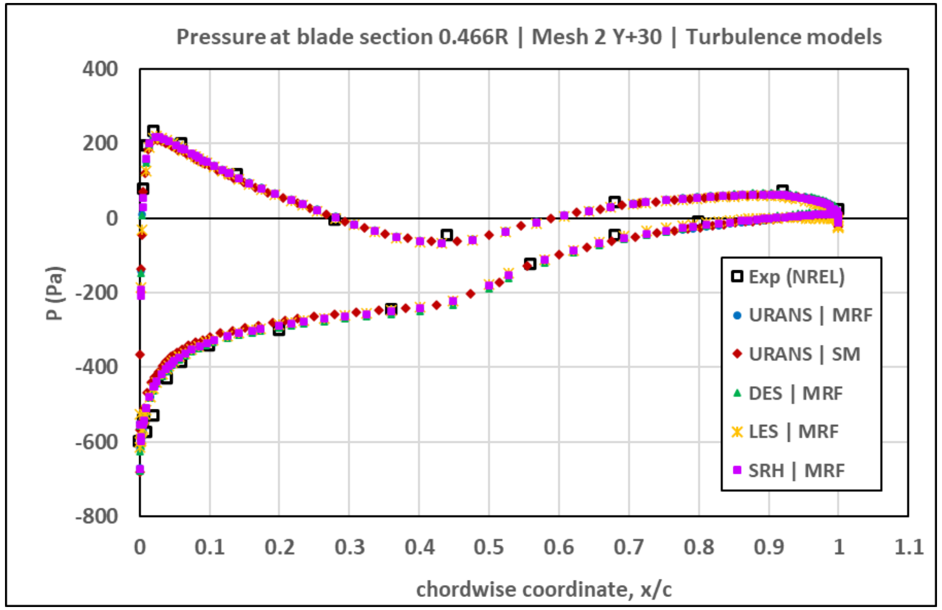
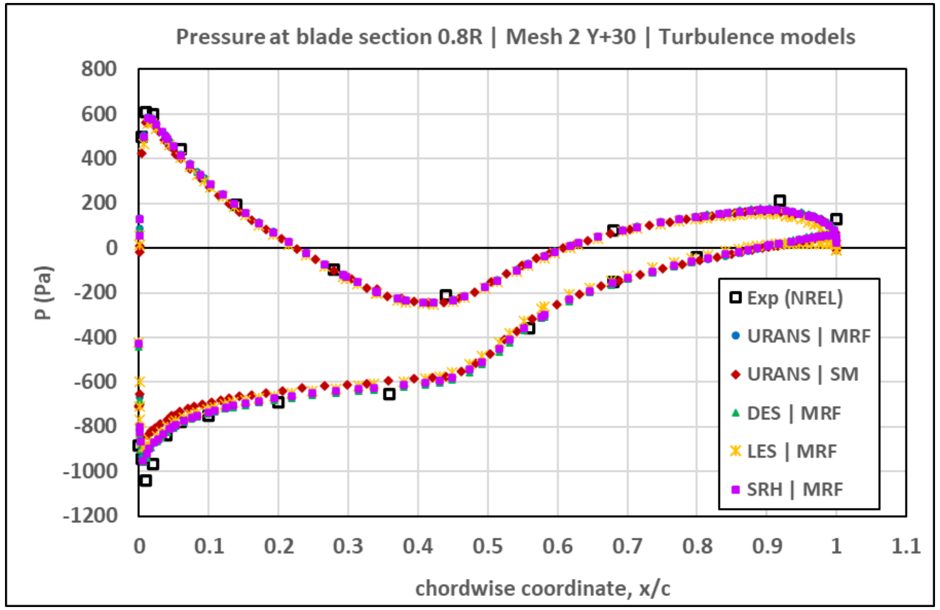
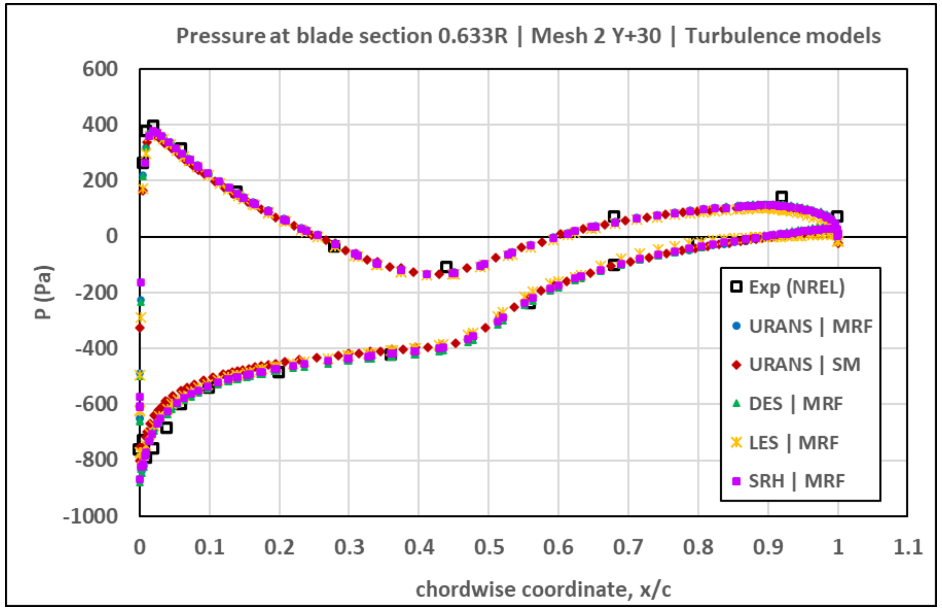
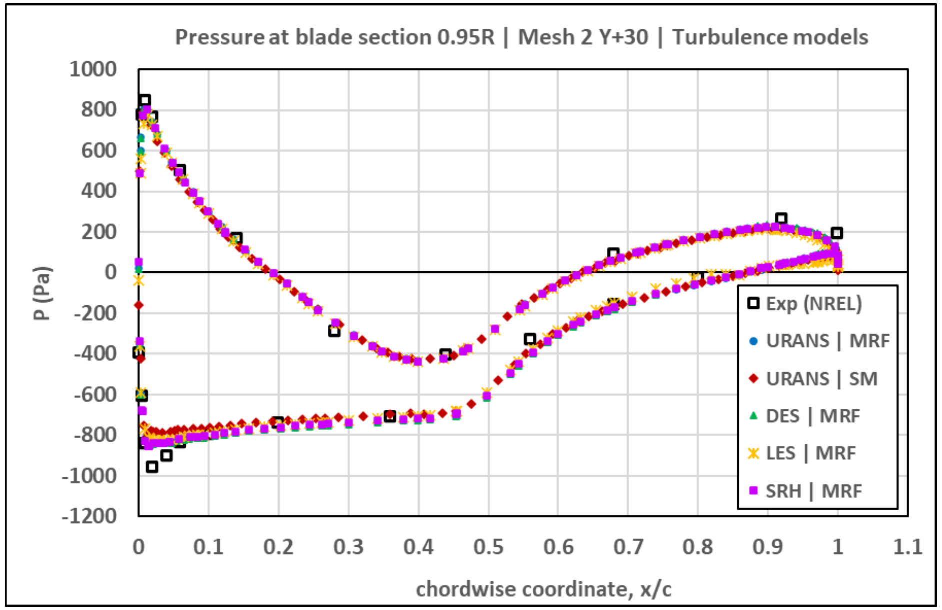
Results regarding different turbulence models | Pressure distributions | V=7 (m/s)









(!) Note:
All pressure distributions are given as instantaneous values from the last simulation time step

MRF – Straight flow setup using Moving Reference Frame
SM – 6DOF setup using Overset Mesh and Sliding Mesh

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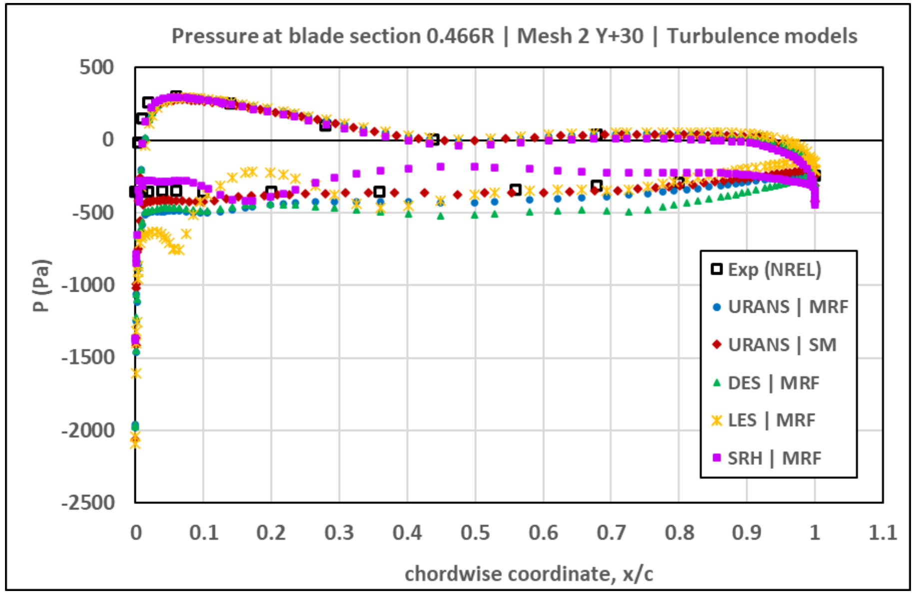
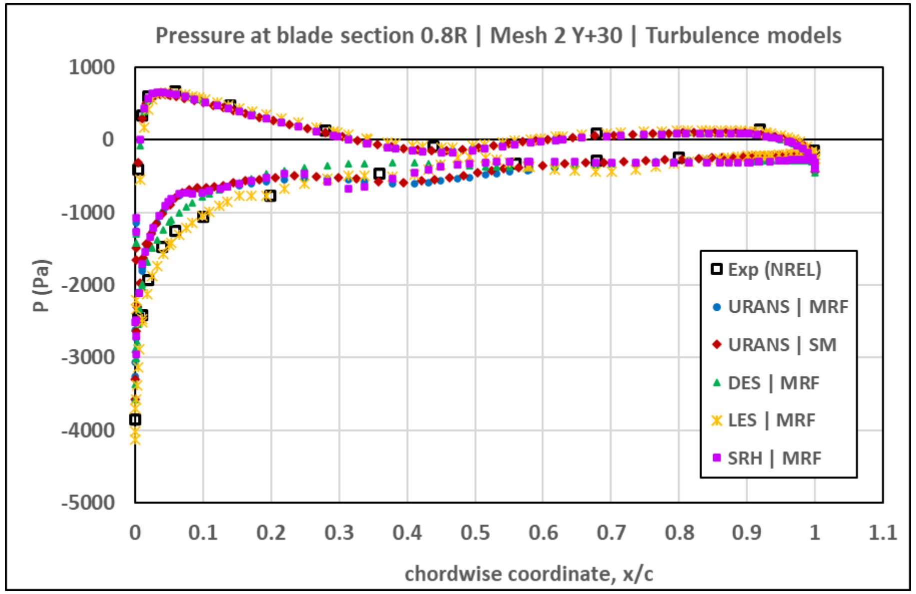
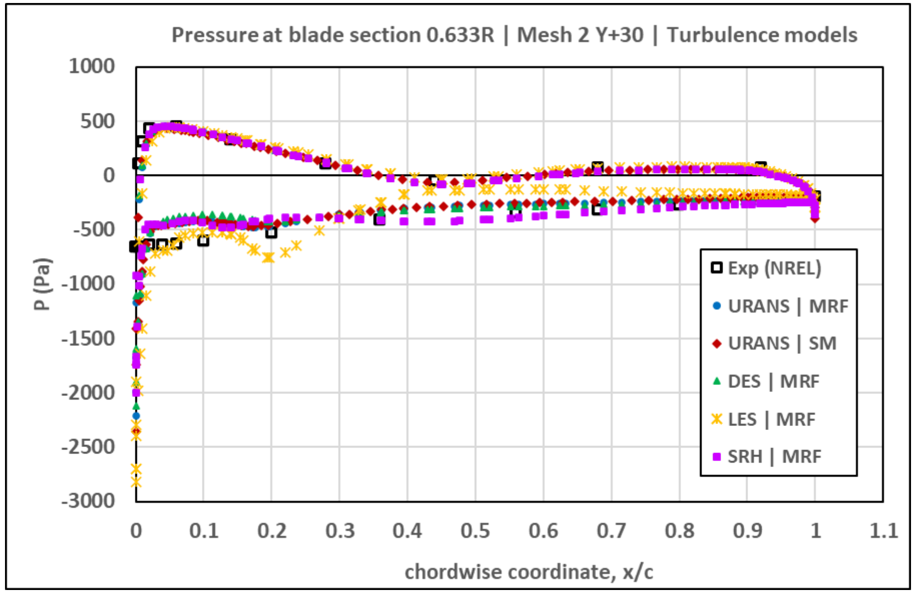
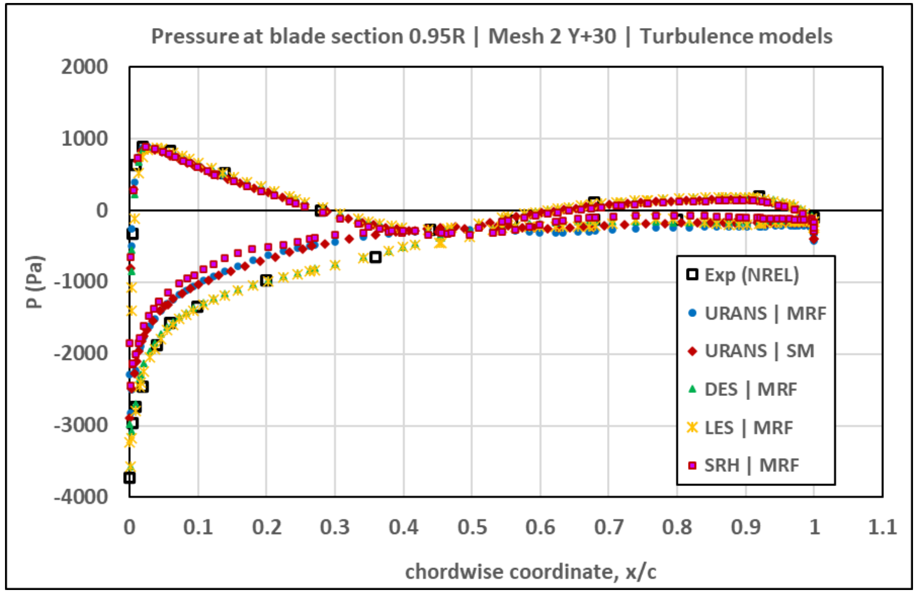
Results regarding different turbulence models | Pressure distributions | V=13 (m/s)





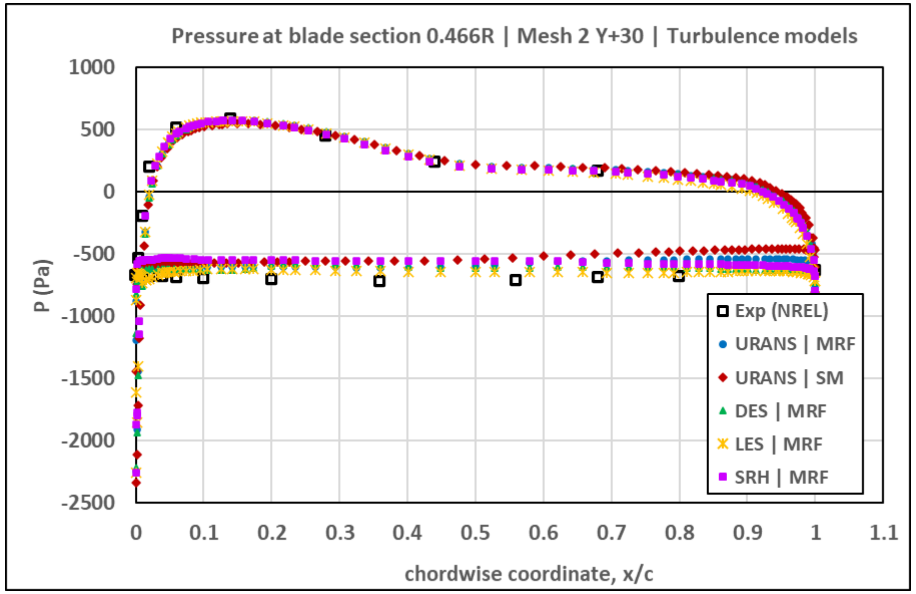


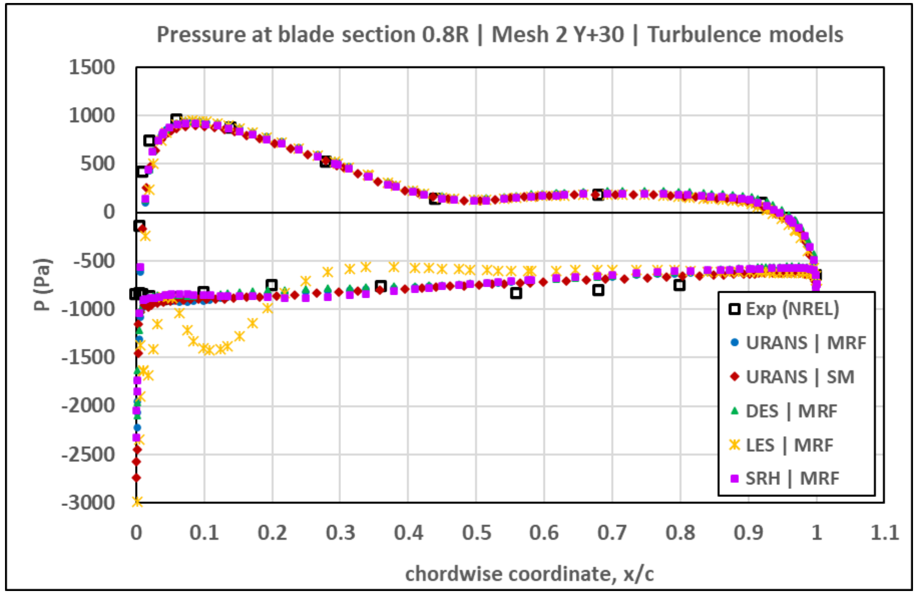


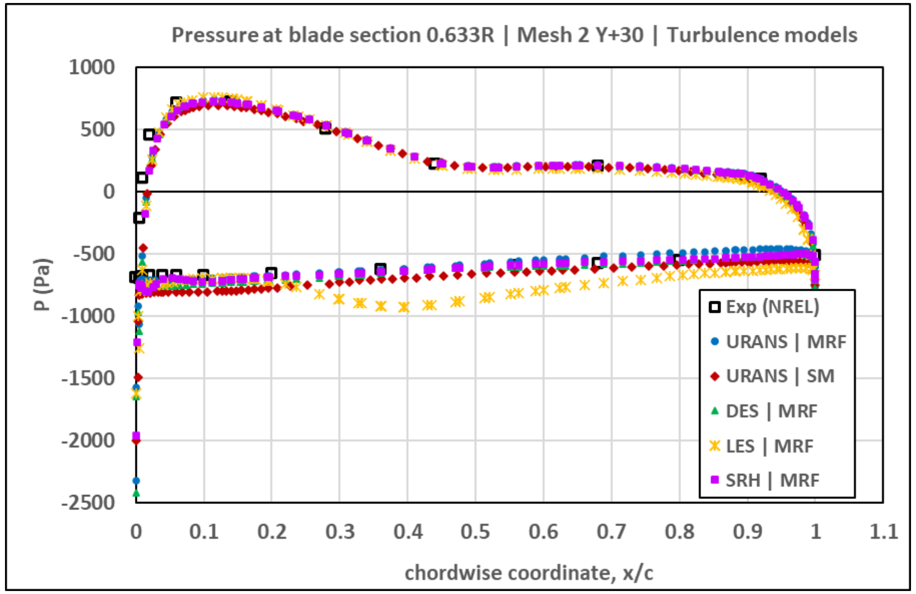
(!) Note:
All pressure distributions are given as instantaneous values from the last simulation time step

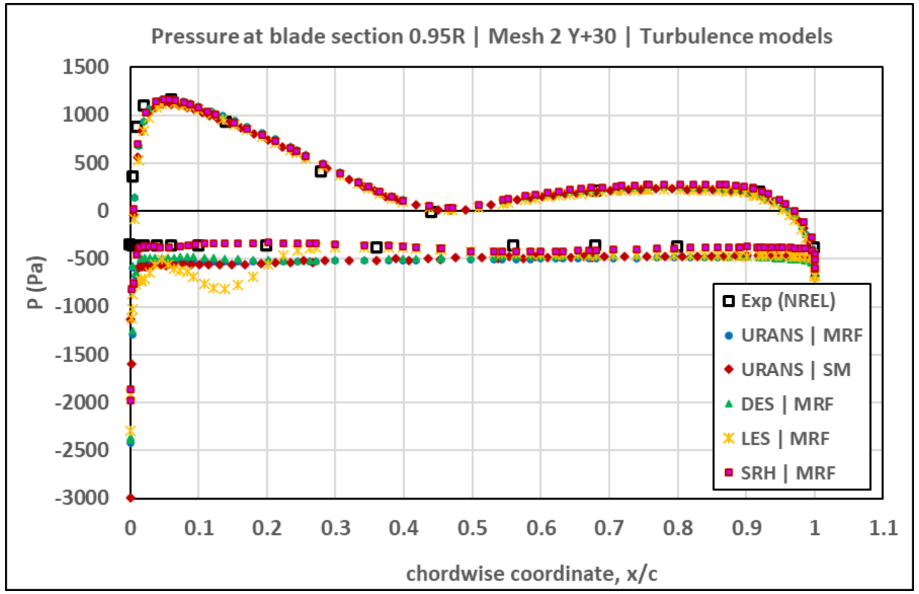
MRF – Straight flow setup using Moving Reference Frame
SM – 6DOF setup using Overset Mesh and Sliding Mesh

Results regarding different turbulence models | Pressure distributions | V=25 (m/s)









(!) Note:
All pressure distributions are given as instantaneous values from the last simulation time step

MRF – Straight flow setup using Moving Reference Frame
SM – 6DOF setup using Overset Mesh and Sliding Mesh

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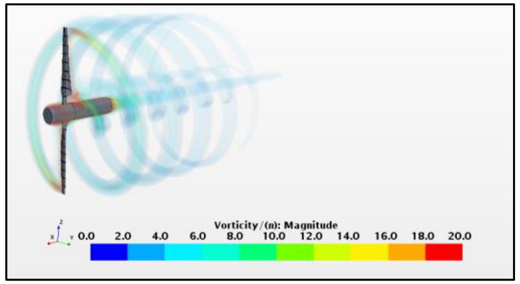
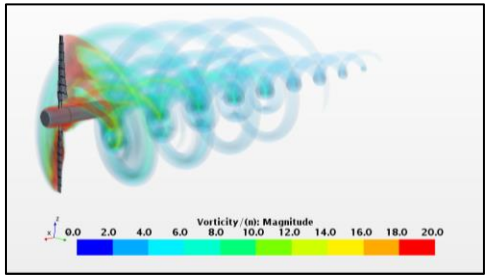
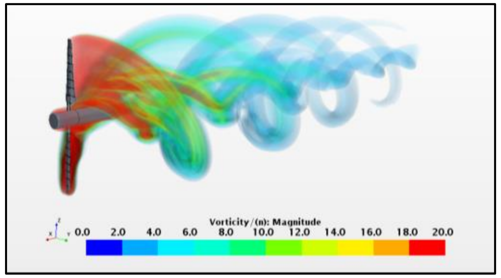
Results regarding different turbulence models | Resolution of rotor wake field

V=7 (m/s) | V=13 (m/s) | V=25 (m/s)

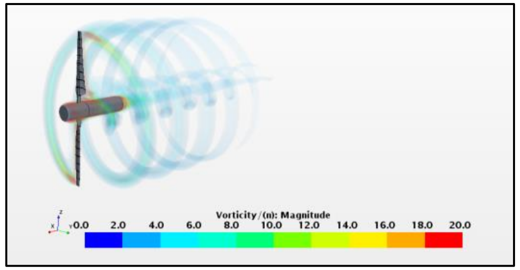
RANS

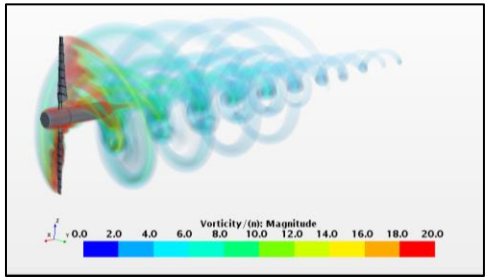


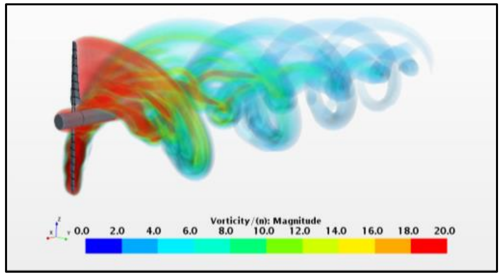




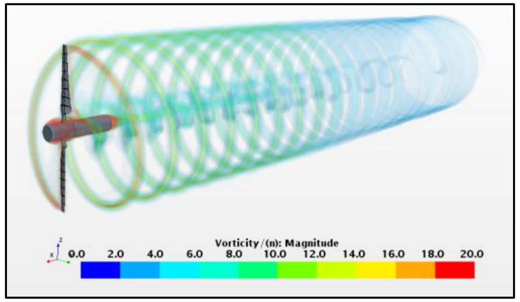
DES

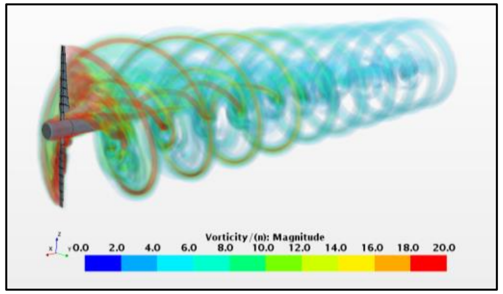


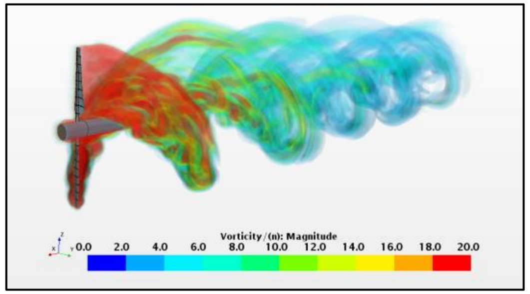




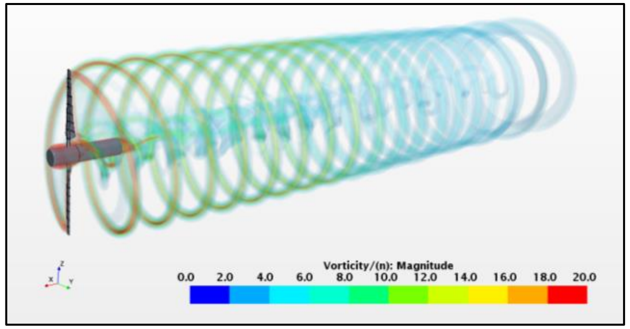
LES

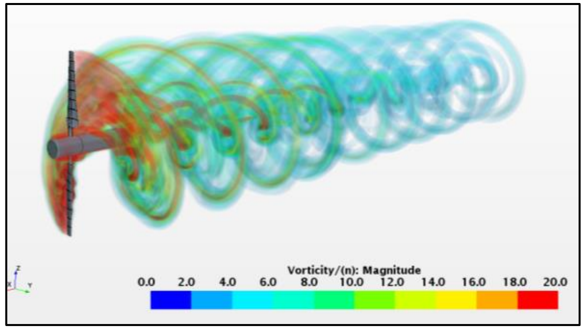


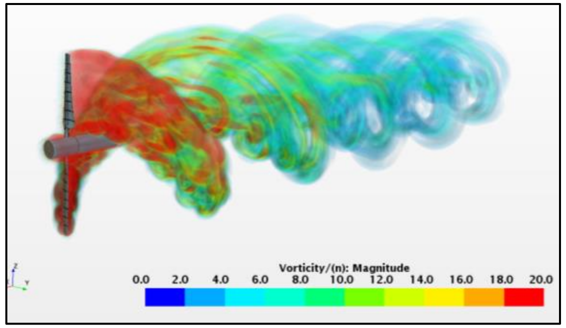




SRH



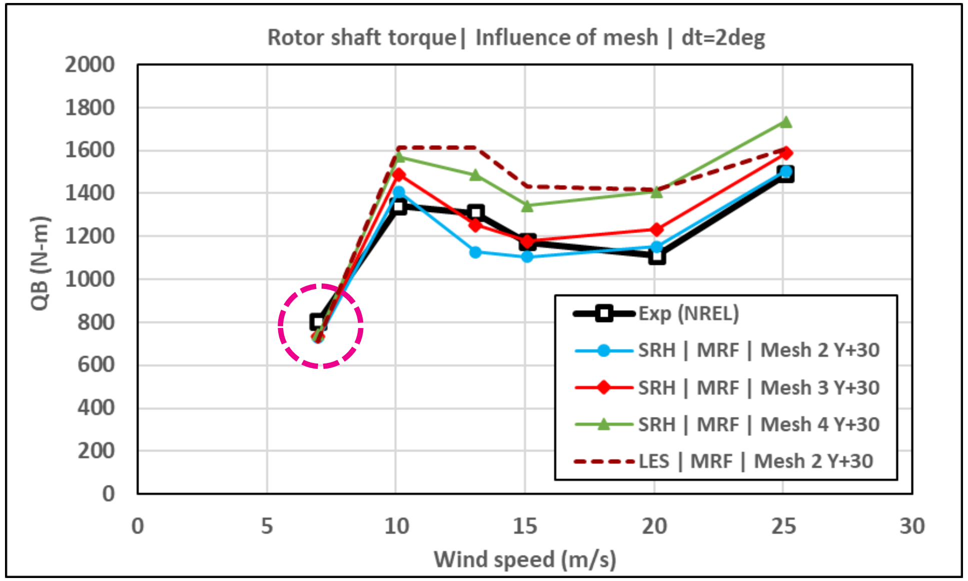


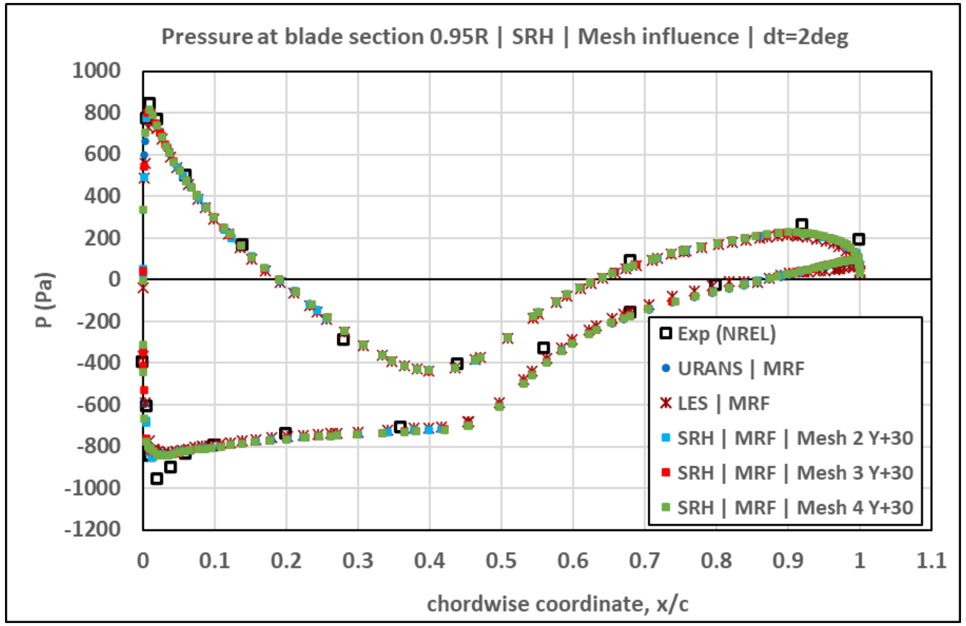


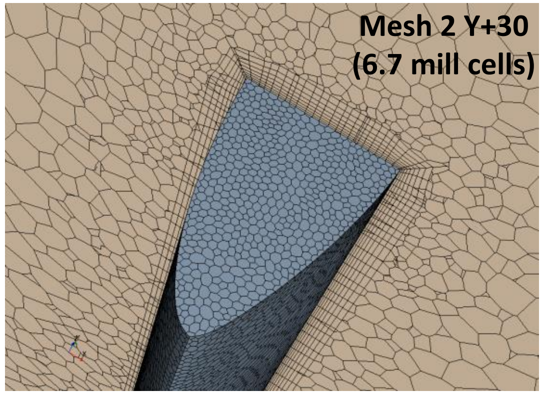
(!) Note:
The images show instantaneous fields of vorticity magnitude from the last simulation time step.
Vorticity magnitude is presented as a non-dimensional quantity related to the rotor rate of revolution, curl(U)/n

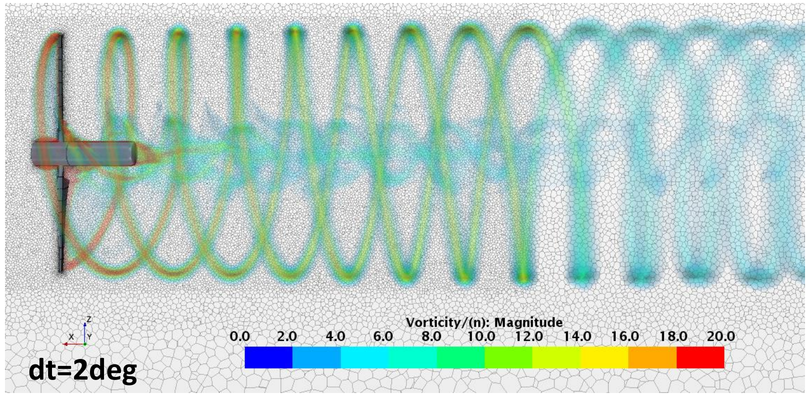
MRF – Straight flow setup using Moving Reference Frame

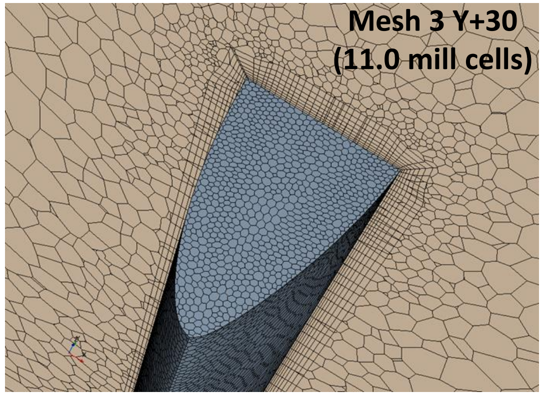
Sensitivity studies with the SRH model | Mesh Refinement | Vs=7 (m/s)

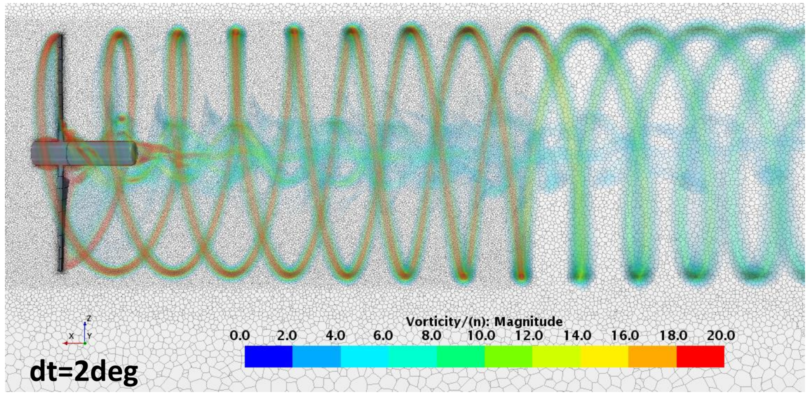


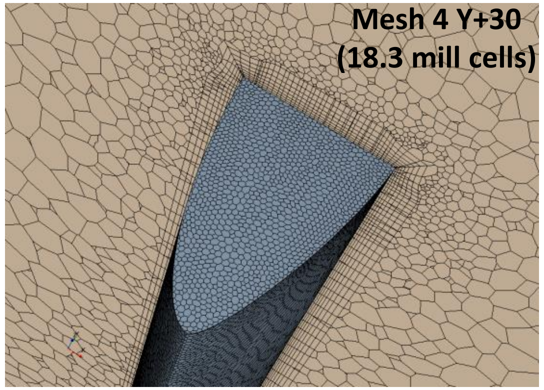


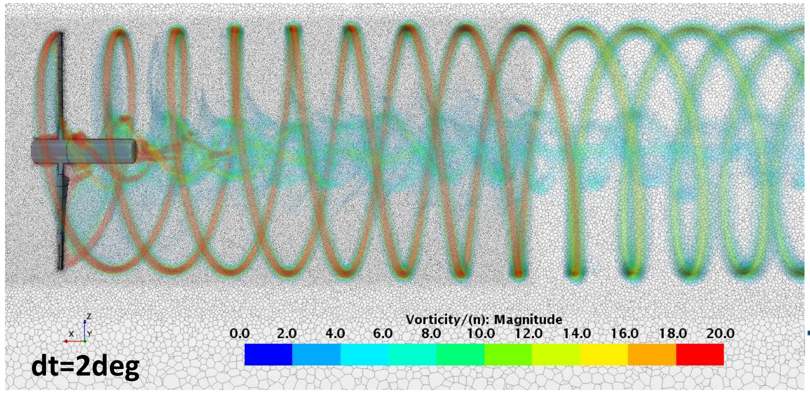






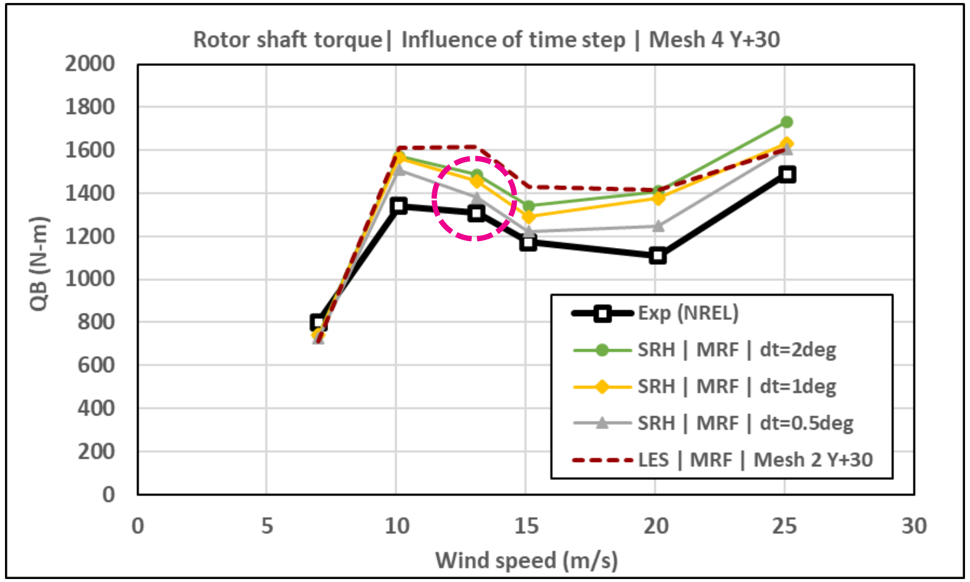


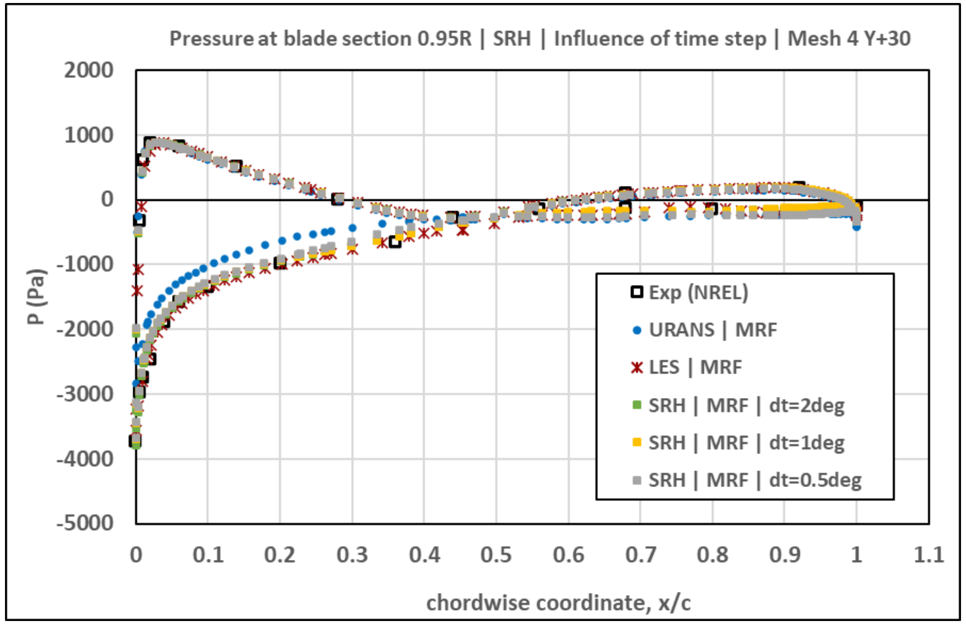




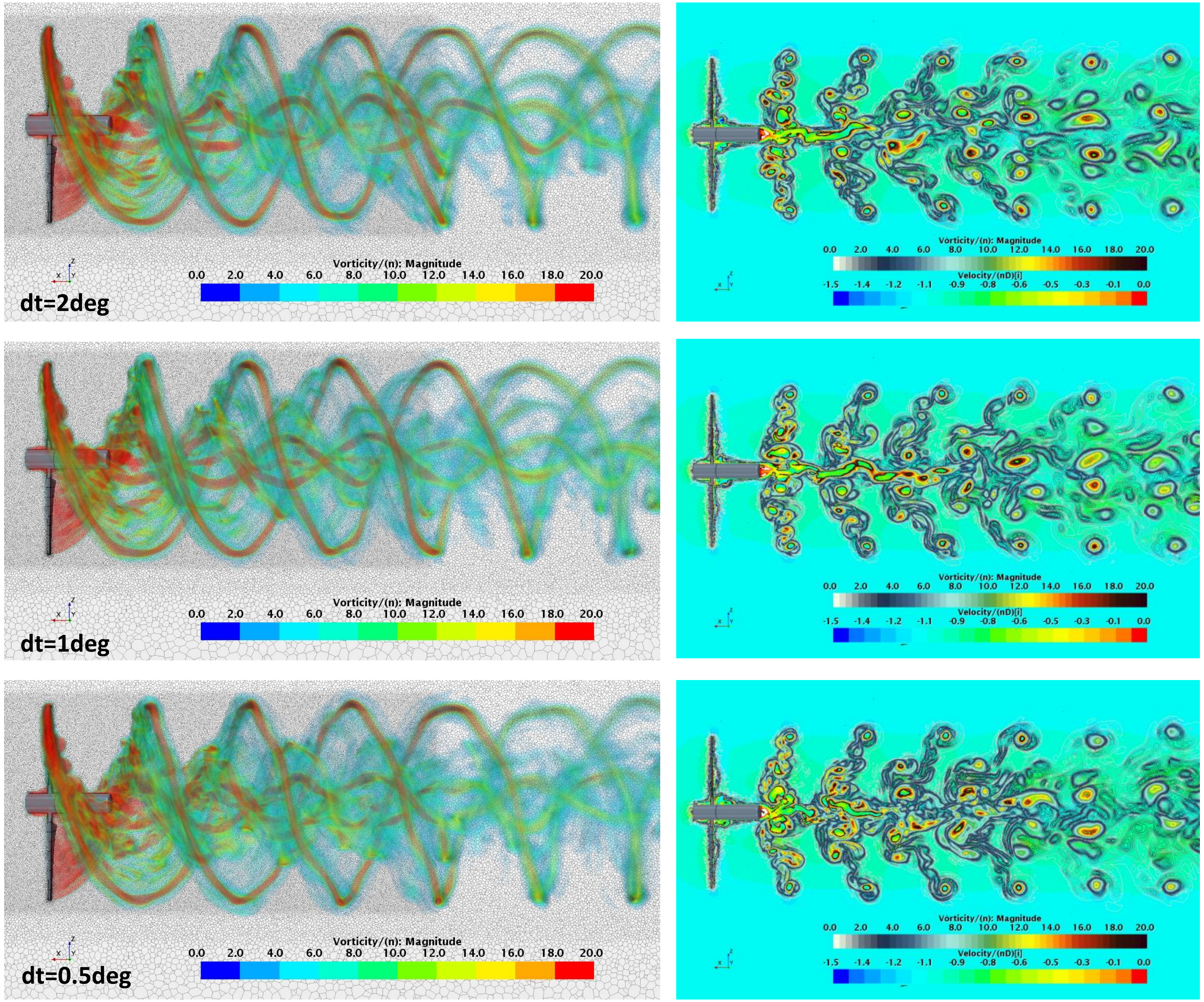
TEF

Sensitivity studies with the SRH model | Variation of time step | Vs=13 (m/s)





Mesh 4 Y+30 (18.3 mill cells)



Conclusions and future work

- A good agreement between the CFD predictions and experimental data in terms of both the integral loads and pressure distribution on the rotor blades is achieved with all different turbulence modelling methods. The only exception is the prediction of rotor torque by LES.
- In general, torque predictions are more sensitive to the modelling approach as well as to the spatial and temporal discretizations compared to thrust, blade bending moment and pressure, which suggests a more significant influence of the field of tangential stress on torque.
- The Scale Resolving/Adaptive Hybrid model (SRH) employed in this work provides a good compromise between the accuracy of load prediction and fidelity of rotor wake resolution, which is comparable to LES.
- A very accurate prediction of pressure distribution at different operation conditions is an essential result for the future analyses of unsteady deformations and associated fatigue loads on the turbine blades by the FSI approach. Scale resolving techniques will be employed for the analysis of dynamic behaviour of the rotor wake and prediction of noise emitted by the turbines.
- Further validation efforts will focus on testing of the SRH model with the generic 6DOF setup, investigations into the low-Re (low Y+) near-wall treatment approach, and comparison with the experiments in terms of velocity field in the rotor wake.

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Teknologi for et bedre samfunn