ISP RAS

NUMERICAL SIMULATION OF PROPELLER HYDRODYNAMICS USING THE OPENFOAM PLATFORM

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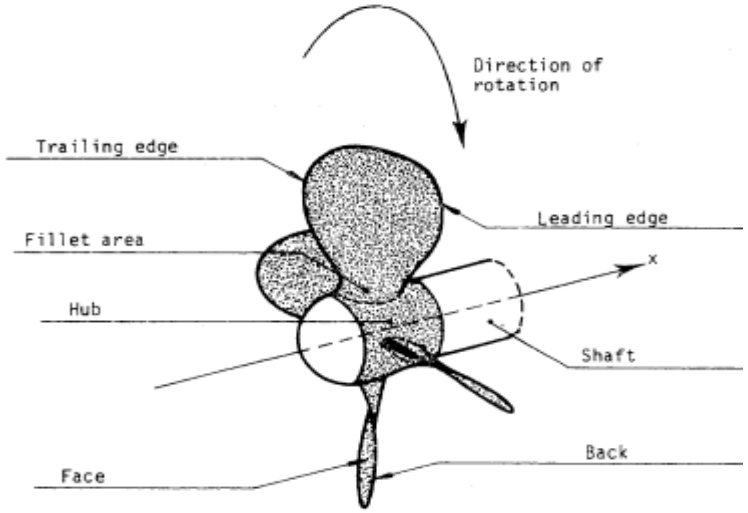
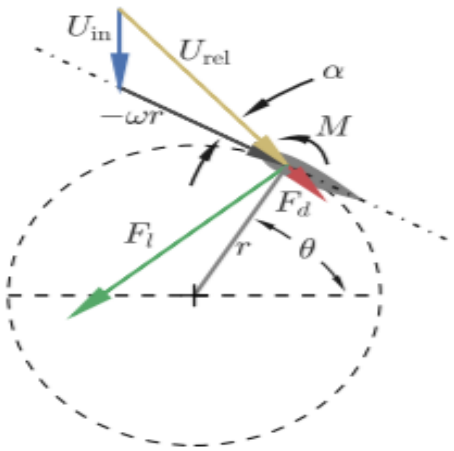
Introduction





ALM forces

TurbinesFoam*

Navier-Stokes equation

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\vec{u} + F_{\text{turbine}}$$

Lift force, drag force, and pitching moment

$$F_l = \frac{1}{2}\rho A_{\text{elem}} C_l |\vec{U}_{\text{rel}}|^2,$$

$$F_d = \frac{1}{2}\rho A_{\text{elem}} C_d |\vec{U}_{\text{rel}}|^2,$$

$$M = \frac{1}{2}\rho A_{\text{elem}} c C_m |\vec{U}_{\text{rel}}|^2,$$

$$\vec{U}_{rel} = \vec{U}_{in} + \overrightarrow{wr}$$

Smoothing function for force and momentum of source

$$\eta = \frac{1}{\epsilon^3 \pi^{3/2}} \exp\left[-\left(\frac{|\vec{r}|}{\epsilon}\right)^2\right]$$

$$\epsilon_{\text{mesh}} = 2C_{\text{mesh}}\Delta x.$$

$$\Delta x \approx \sqrt[3]{V_{\text{cell}}},$$

Unsteady effects:

- Dynamic stall;
- Added mass.

*https://github.com/turbinesFoam/turbinesFoam

Initial data for the library

Initial data for the library is:

- File with parameters for ALM:
  - *Axial distance for element;*
  - *Radius of element;*
  - *Azimuth of element;*
  - *Value of element`s chord;*
  - *Chord mount (by the default quarter-chord);*
  - *Twist.*
- Origin and direction of coordinate system;
- Rotor radius;
- Number of blades;
- The angular speed of rotation of the rotor.

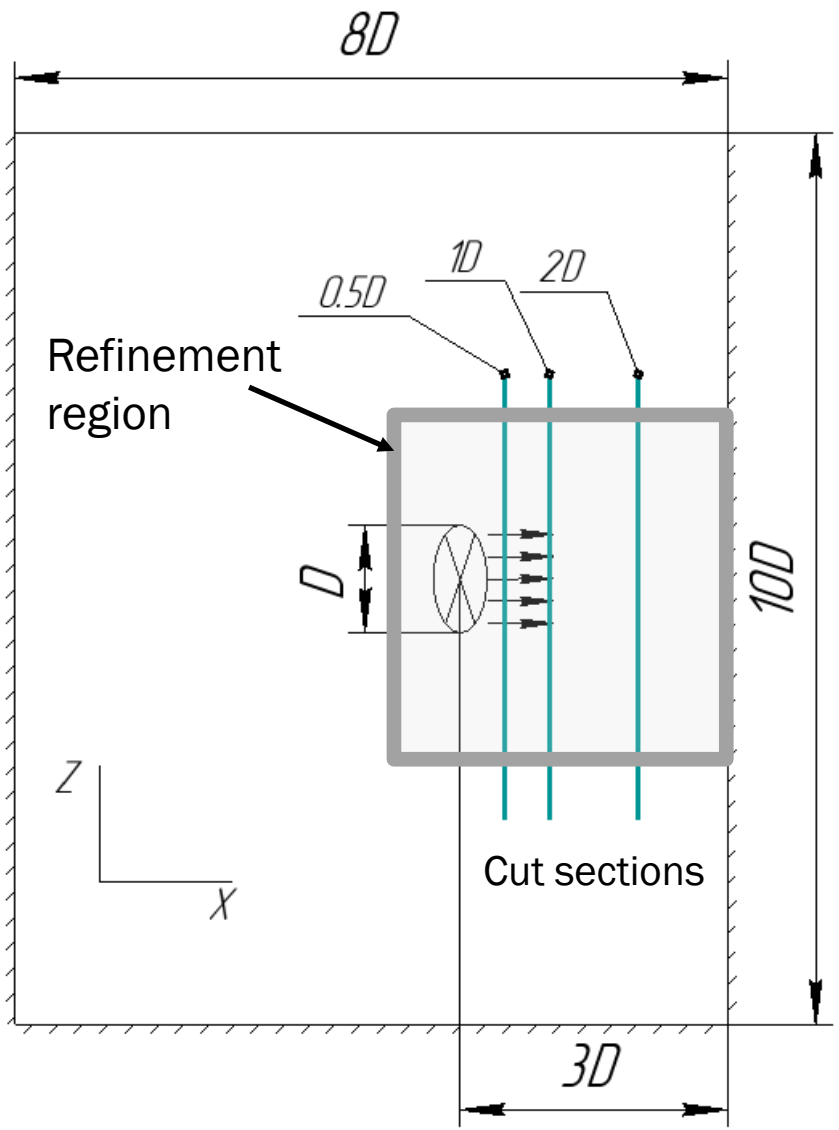
Example of the file with element parameters :

```
// Blade element data
// axialDistance, radius, azimuth, chord, chordMount, twist
(0.0    0.01     0.0    0.020145    0.25     53.52825213)
(0.0    0.015    0.0    0.022977    0.25     42.04660568)
(0.0    0.02     0.0    0.025557    0.25     34.07475497)
(0.0    0.025    0.0    0.027903    0.25     28.41900823)
(0.0    0.03     0.0    0.03        0.25     24.27247059)
(0.0    0.035    0.0    0.031758    0.25     21.13247156)
(0.0    0.04     0.0    0.033024    0.25     18.6857556)
(0.0    0.045    0.0    0.033798    0.25     16.7321444)
(0.0    0.05     0.0    0.033864    0.25     15.13965812)
```

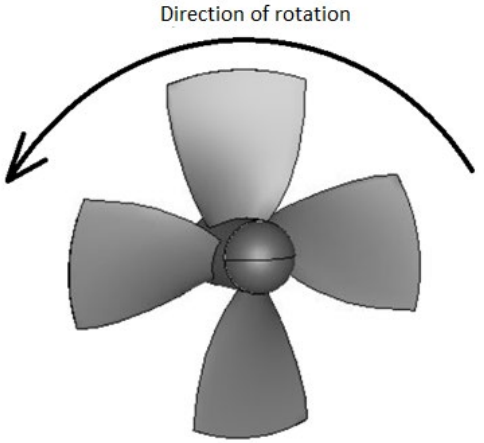
In addition to geometric parameters, each element corresponds to a certain profile, which has its own aerodynamic characteristics.

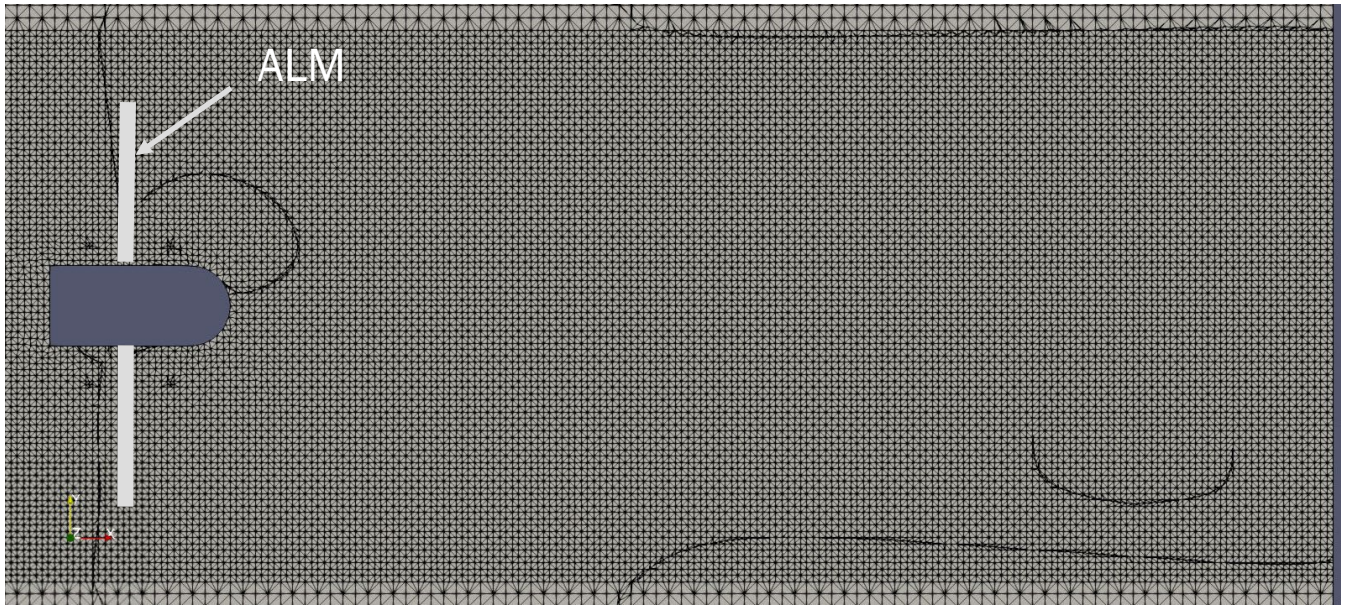
For each blade the number of elements is specified, as well as the profile corresponding to each elements.

Problem statement



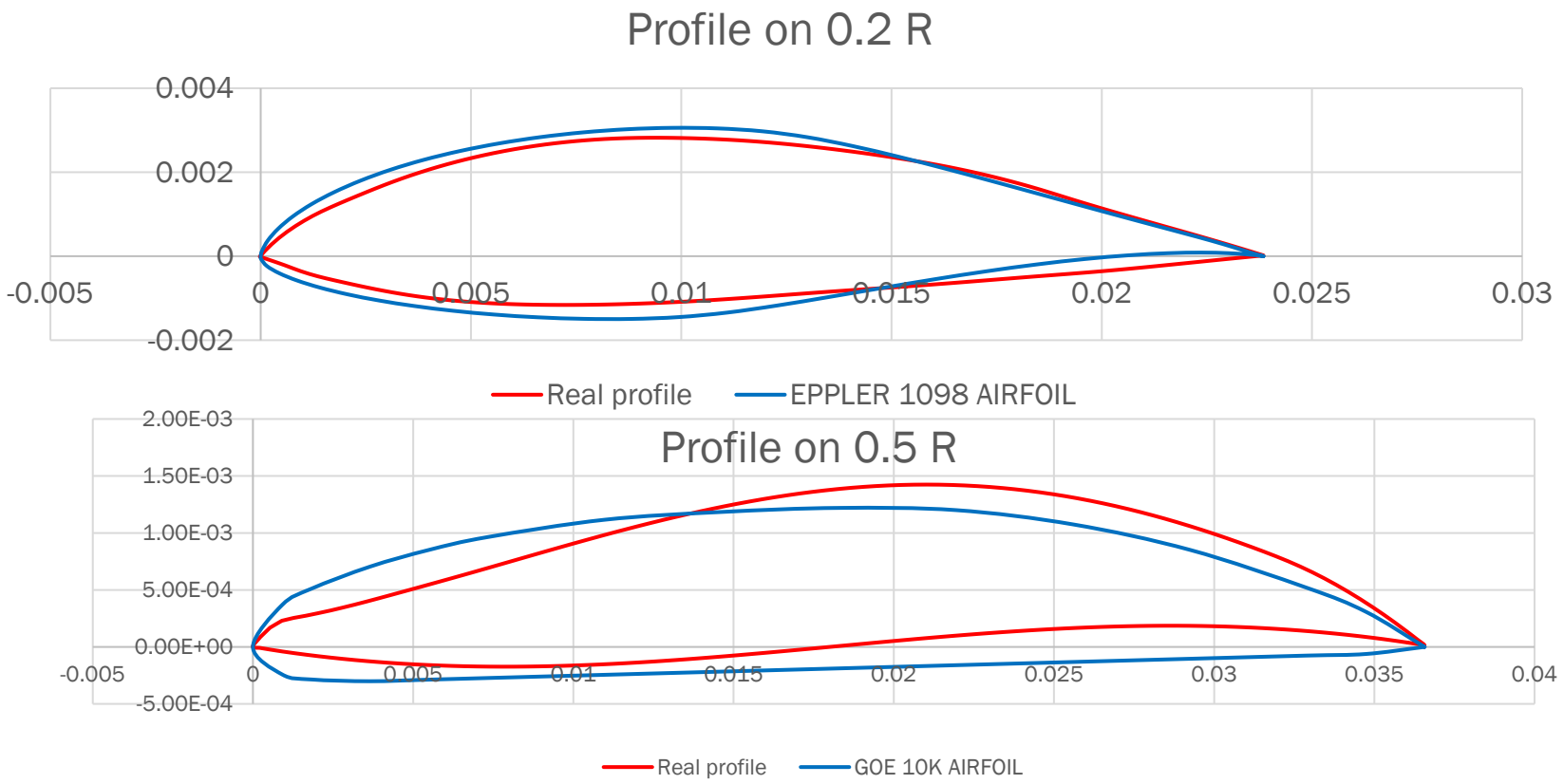
- Library turbinesFoam;
- Turbines diameter D = 0.1 m.;
- Propeller Ka4-70;
- The angular speed of rotation of the rotor is 500 RPM.
- Coarse mesh – 1.5 x 10e6
- Fine mesh – 12 x 10e6



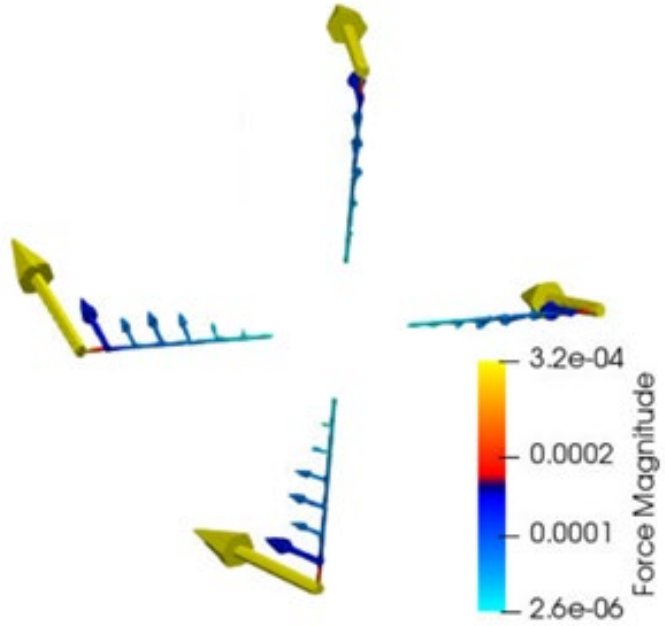


Coarse mesh fragment with hub model

Profiles choosing



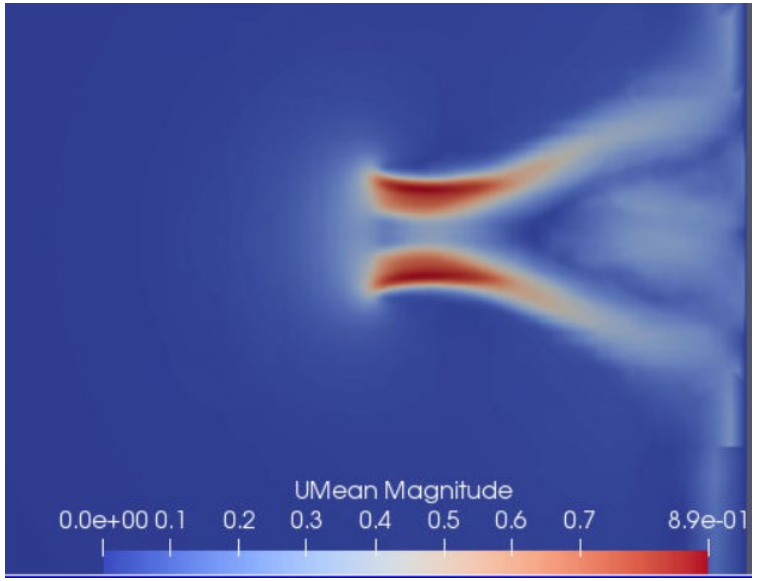
ALM model
with 8 elements



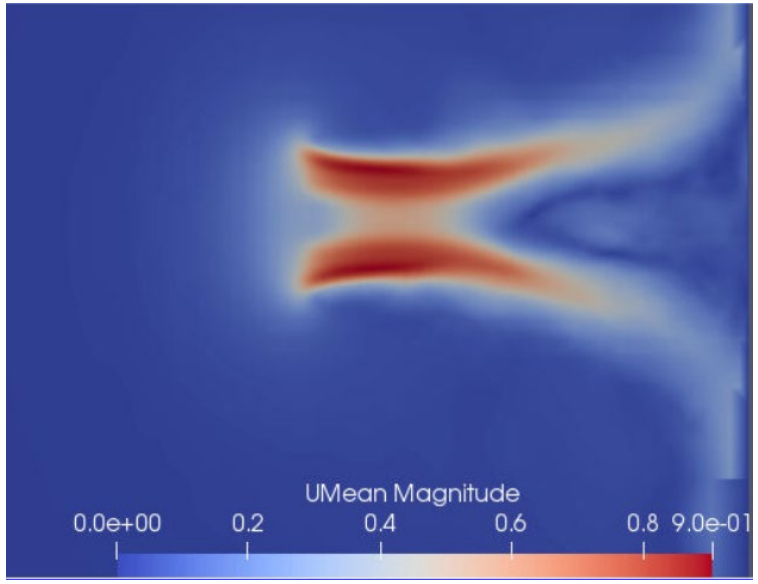
Name of profile	Radius of element	Chord	Twist
EPPLER 1098 AIRFOIL	0.01	0.02	53.53
S4402	0.015	0.023	42.05
EPPLER 908 AIRFOIL	0.02	0.026	34.07
EPPLER 908 AIRFOIL	0.025	0.028	28.42
GOE 492 AIRFOIL	0.03	0.03	24.27
GOE 10K AIRFOIL	0.035	0.032	21.13
GOE 5K AIRFOIL	0.04	0.033	18.69
GOE 9K AIRFOIL	0.045	0.034	16.73
NASA SC(2)-0402 AIRFOIL	0.05	0.034	15.14

Number of elements influence

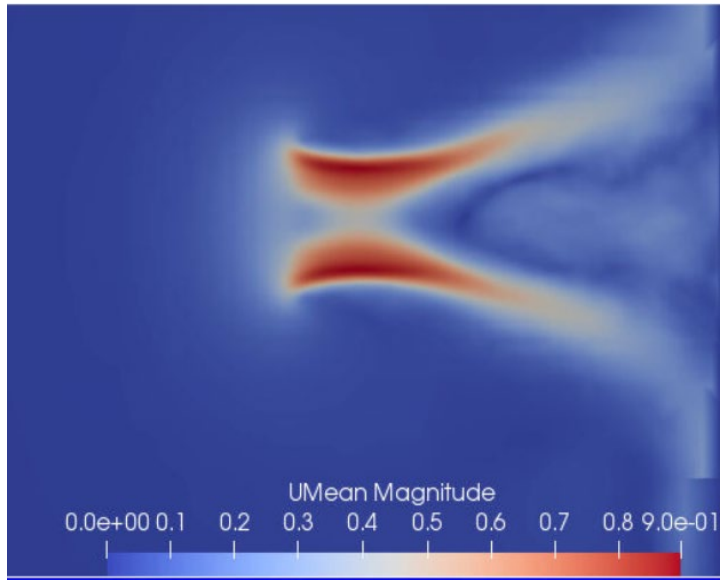
8 elements flow structure:



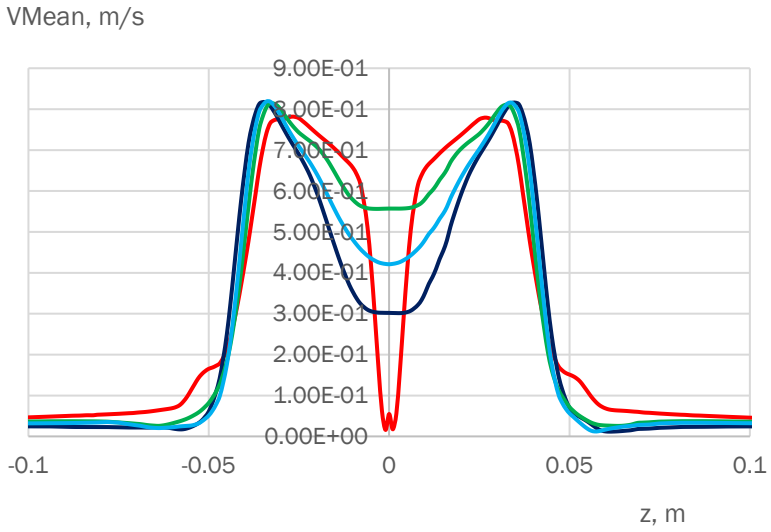
16 elements flow structure:



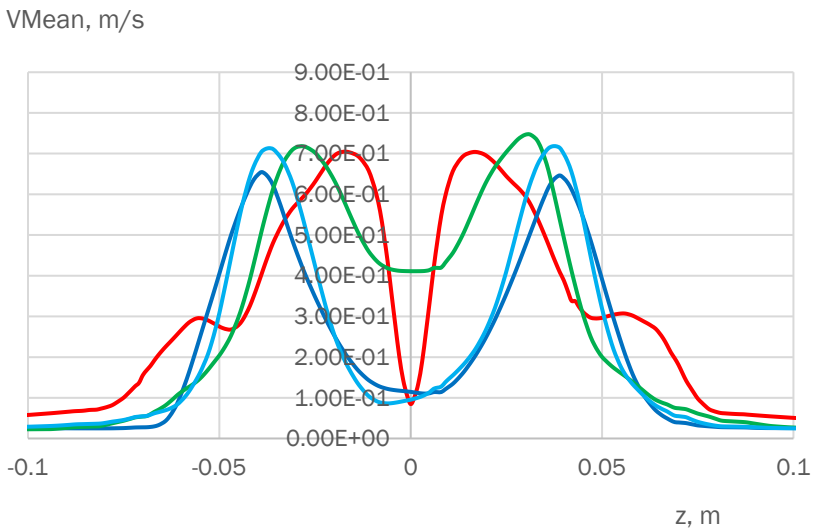
32 elements flow structure:



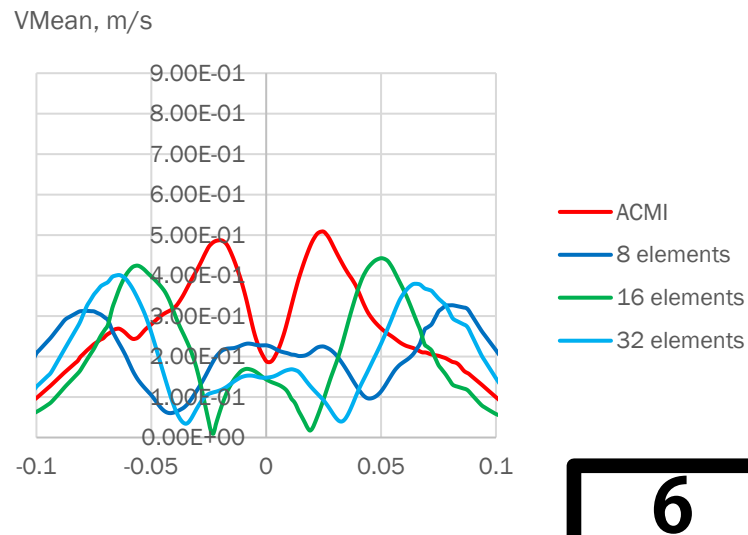
Comparing of mean velocity on 0.5D



Comparing of mean velocity on 1D

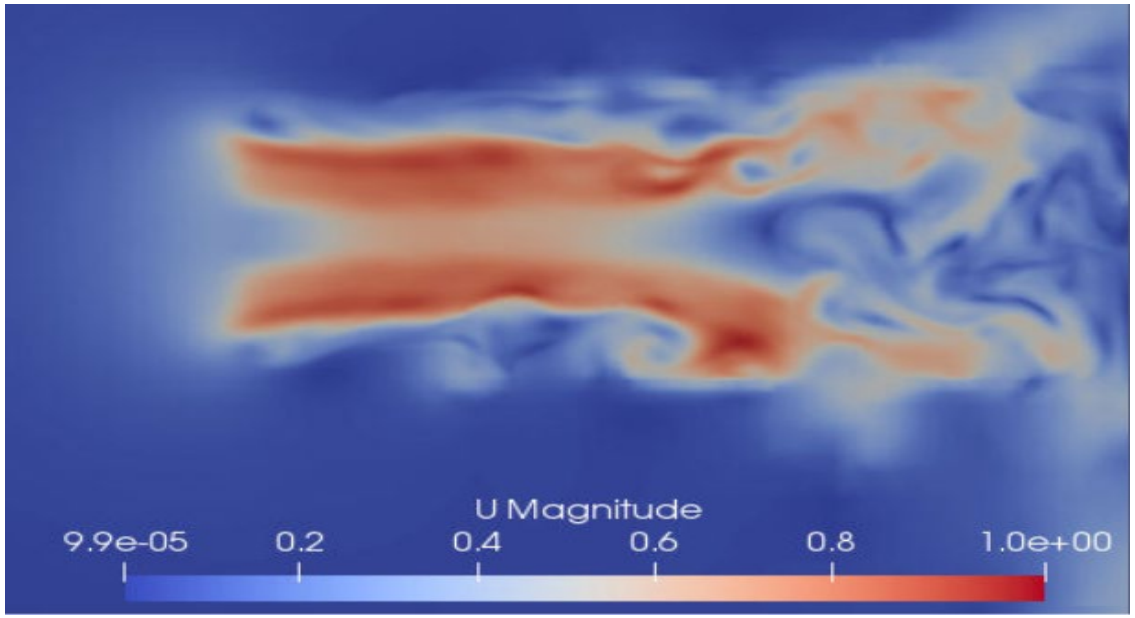


Comparing of mean velocity on 2D

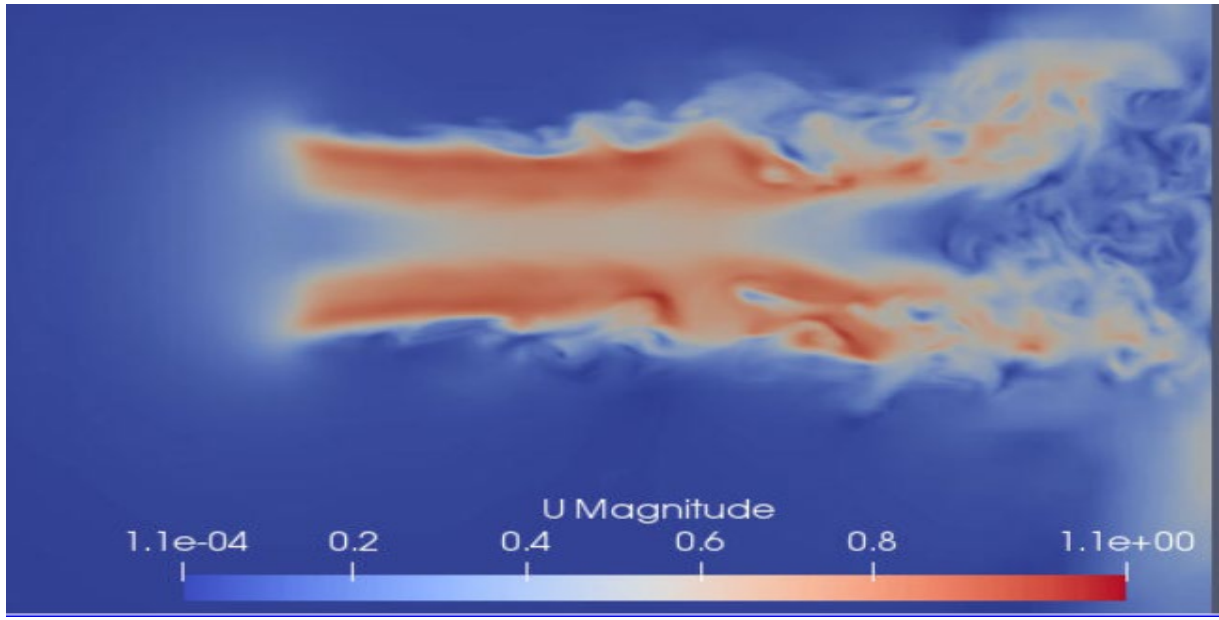


Mesh resolution influence

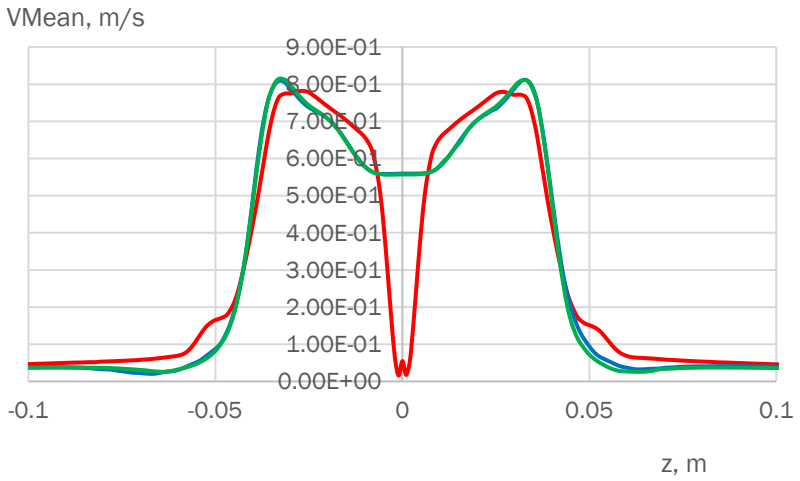
16 elements flow structure on coarse mesh:



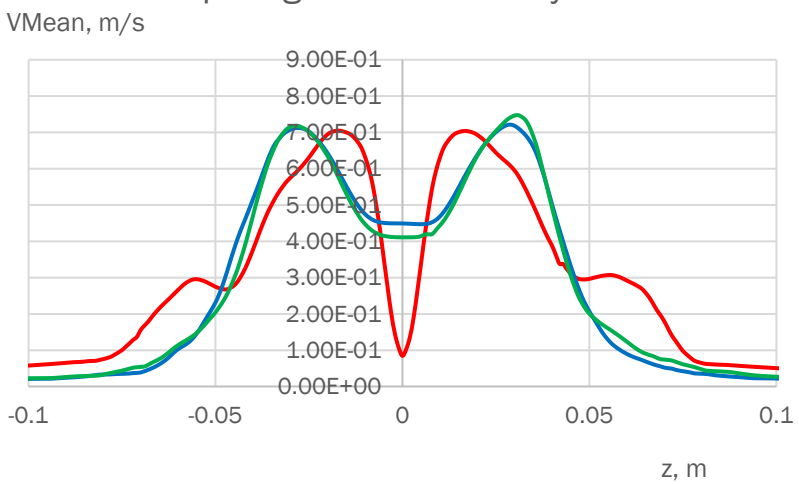
16 elements flow structure on finest mesh:



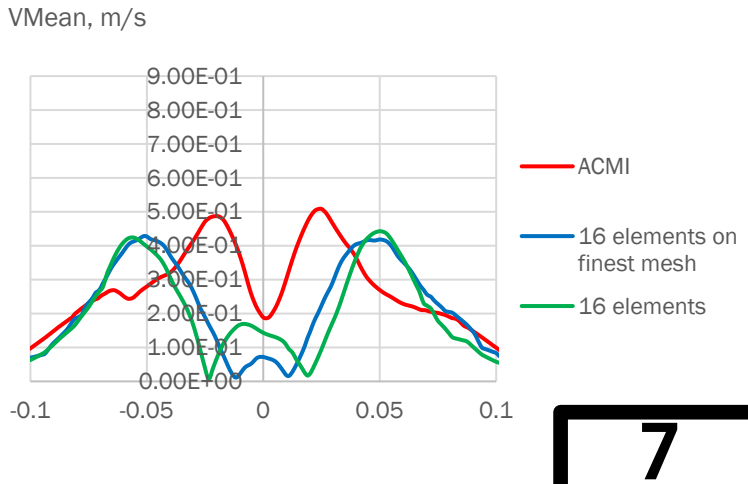
Comparing of mean velocity on 0.5D



Comparing of mean velocity on 1D

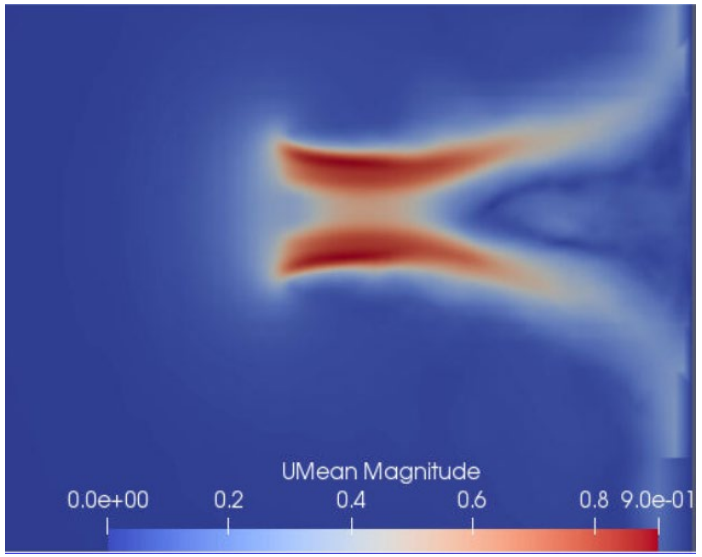


Comparing of mean velocity on 2D

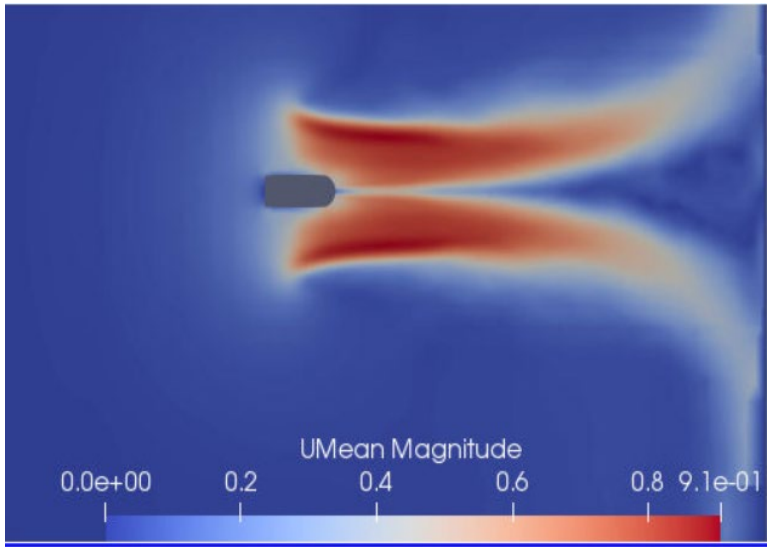


Hub influence

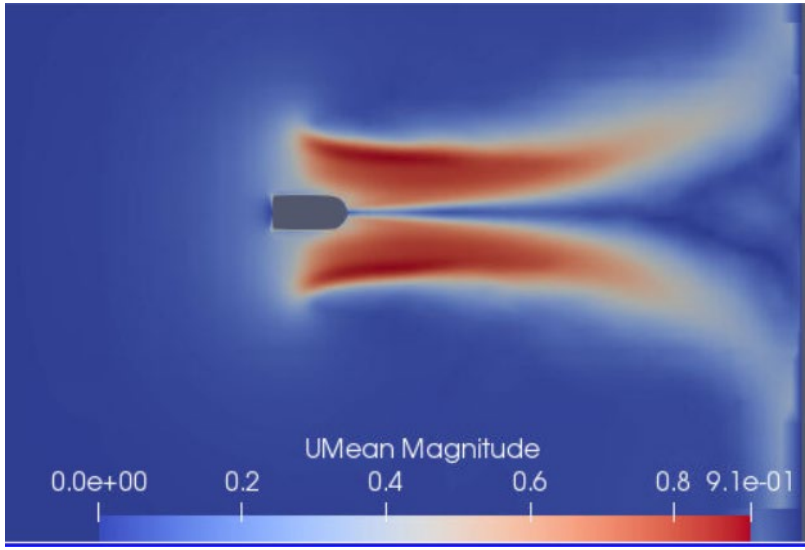
Flow structure without hub(16 elements):



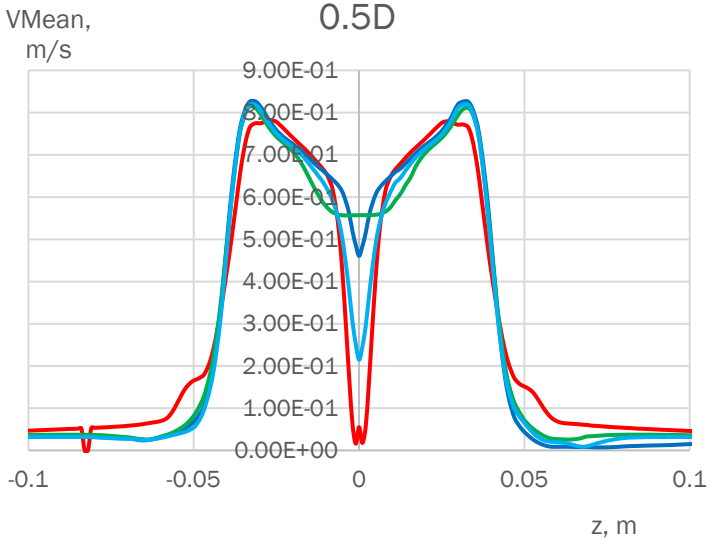
Fixed hub flow structure:



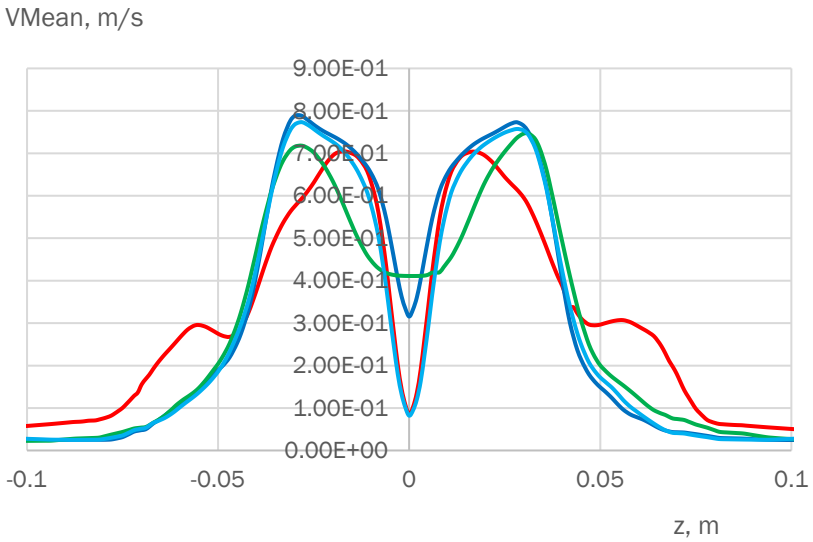
Rotating hub flow structure:



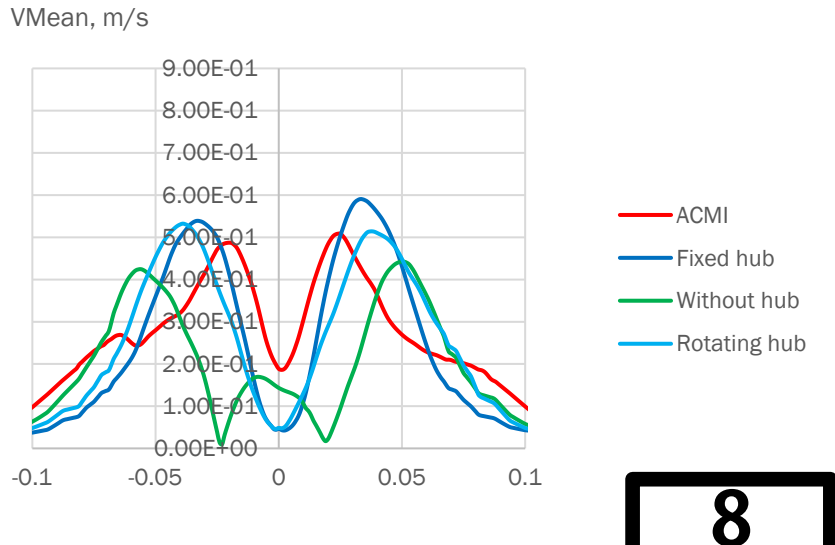
Comparing of mean velocity on 0.5D



Comparing of mean velocity on 1D

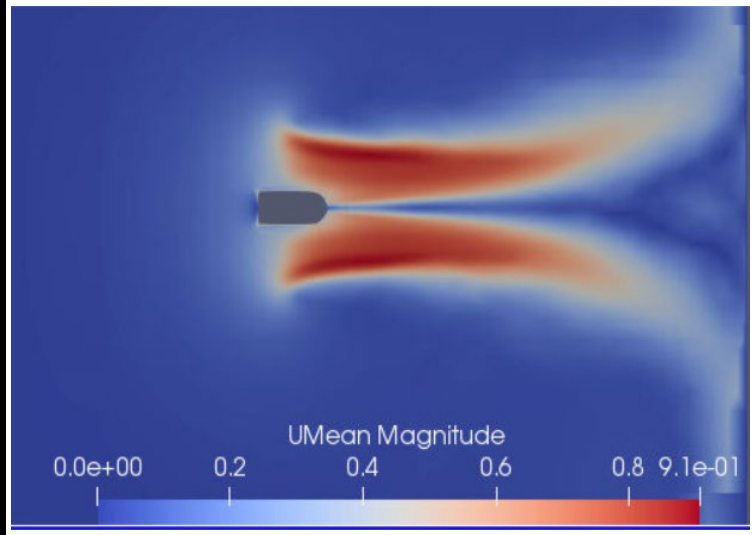


Comparing of mean velocity on 2D

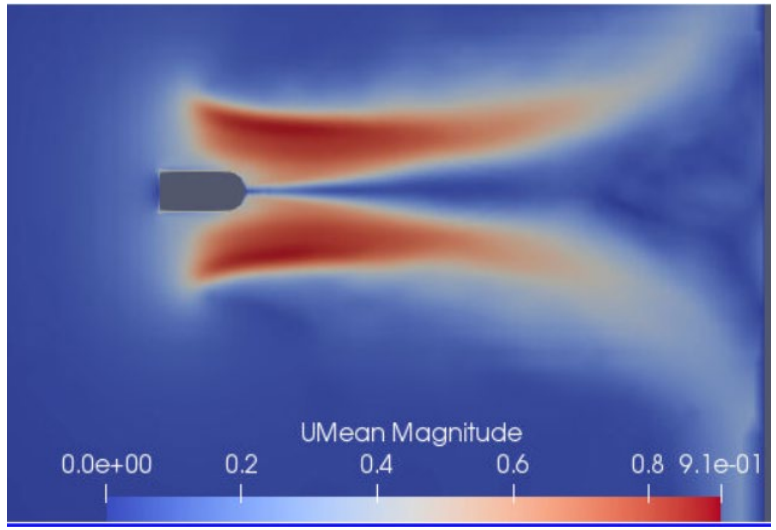


End effects influence

Rotating hub flow structure:



Rotating hub with end effects flow structure:



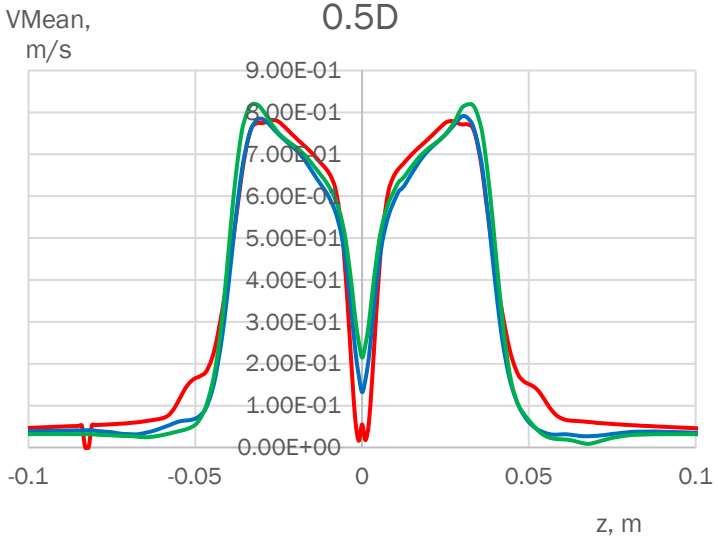
Glauert correction:

$$F = \frac{2}{\pi}\cos^{-1} e^{-f}$$

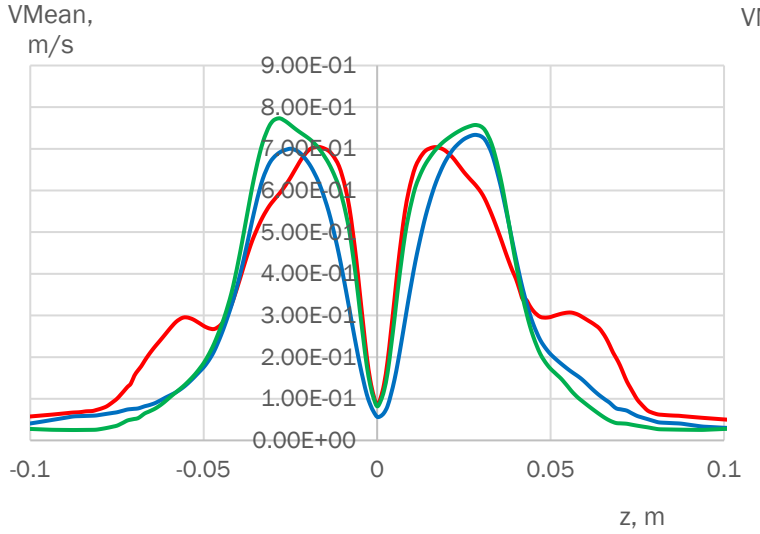
$$\mathrm{f} = \frac{\mathrm{B}}{2}\frac{R-r}{r sin\varphi},$$

where B – number of blades, R – radius of blade, r – radius of element, φ – blade flow angle

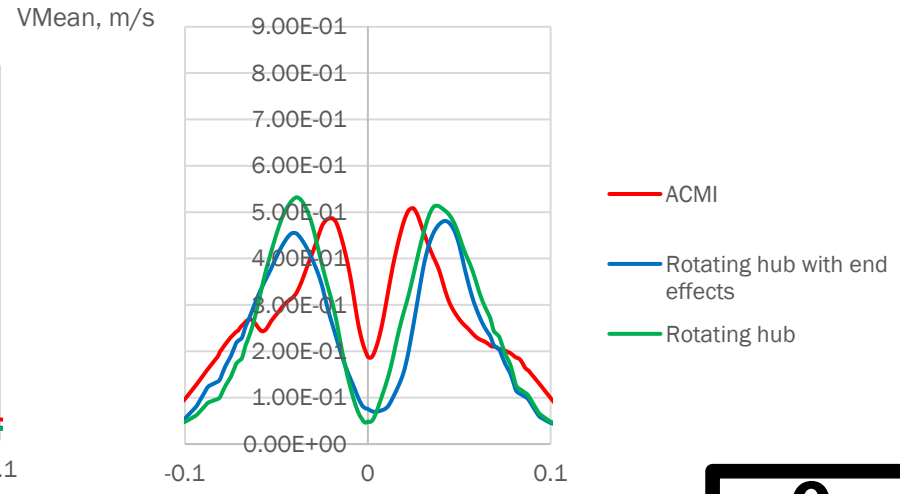
Comparing of mean velocity on 0.5D



Comparing of mean velocity on 1D

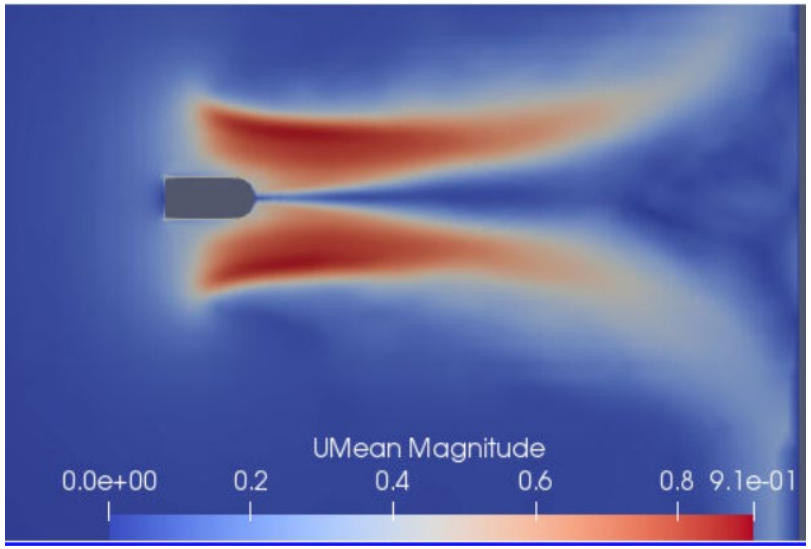


Comparing of mean velocity on 2D

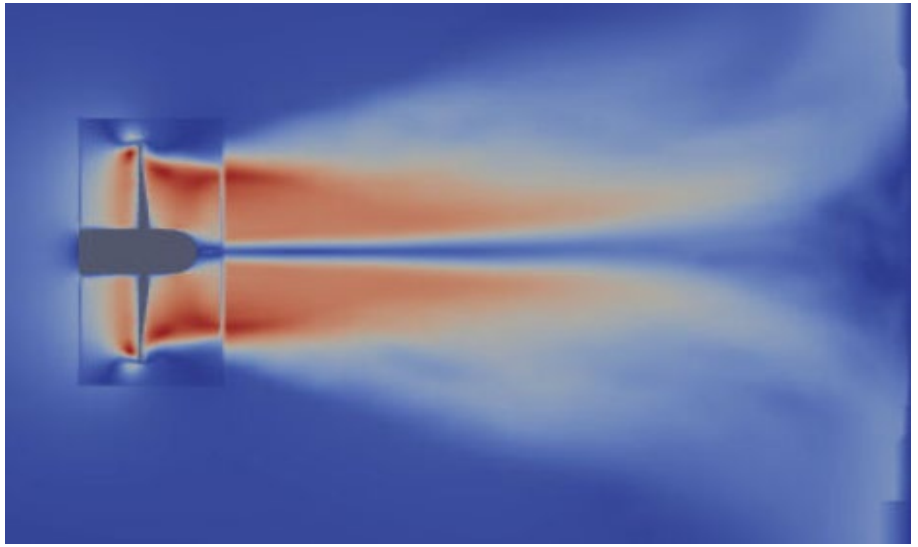


Comparison with experiment

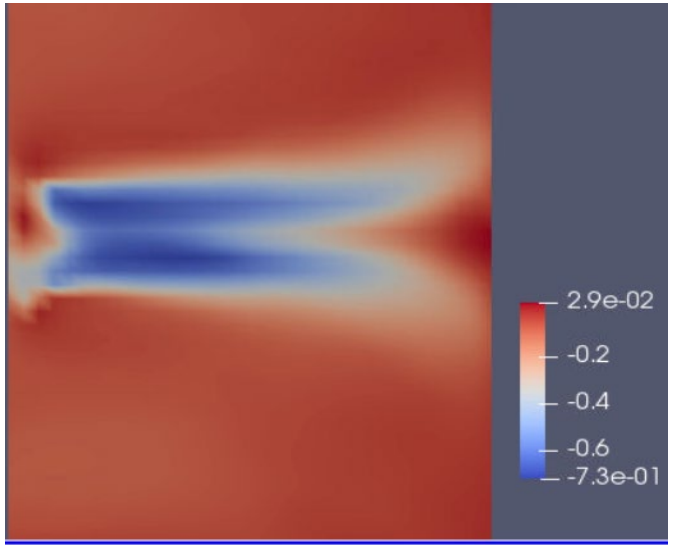
Rotating hub with end effects flow structure :



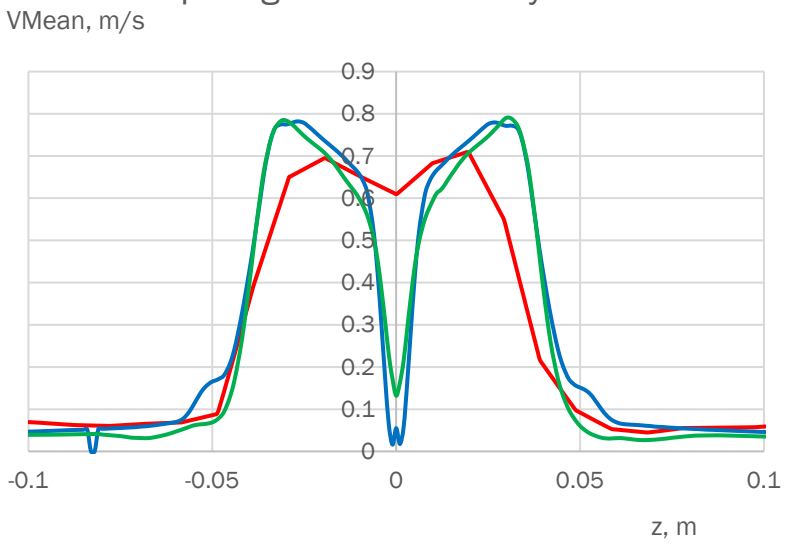
ACMI modeling flow structure:



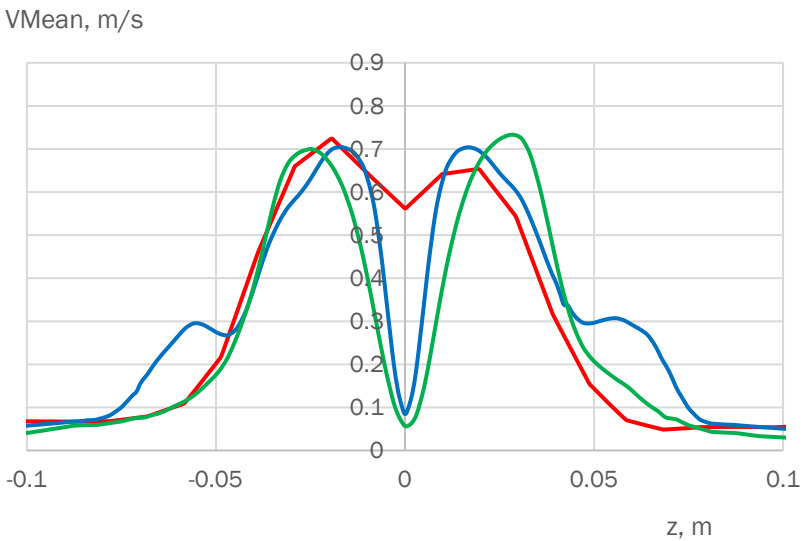
Experiment flow structure:



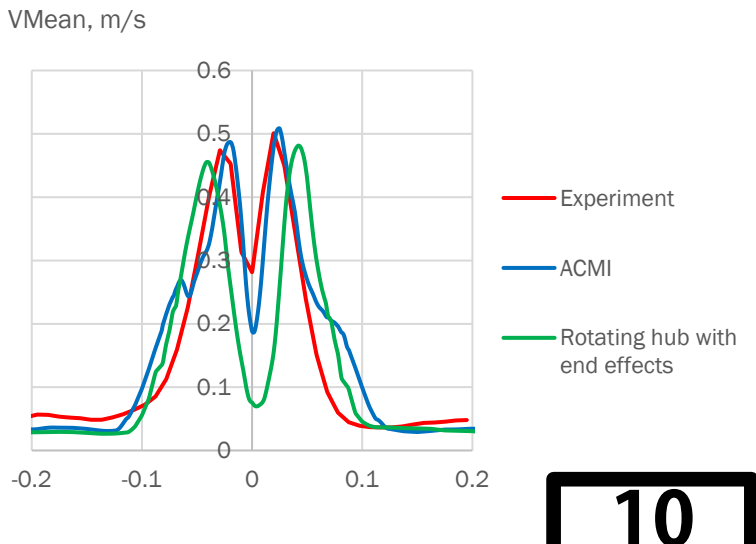
Comparing of mean velocity on 0.5D



Comparing of mean velocity on 1D



Comparing of mean velocity on 2D



Conclusion

- The turbinesFoam library has been modified. This made It possible to simulate turbines in the generator mode.
- The application of actuator line model (ALM) reduces the calculation time of the one iteration in comparison with the ACMI approach by 3 times;
- A decrease of the grid cell size in the flow region affected the instantaneous structure of the velocity field, but the mean velocity changed insignificantly.
- It is necessary to take into account the presence of a propeller hub in the numerical simulation.
- The simulation with the end effects model brings ALM results closer to the ACMI approach and experimental data.