Simulation of flow near rotating propeller defined by immersed boundary method on adaptive meshes

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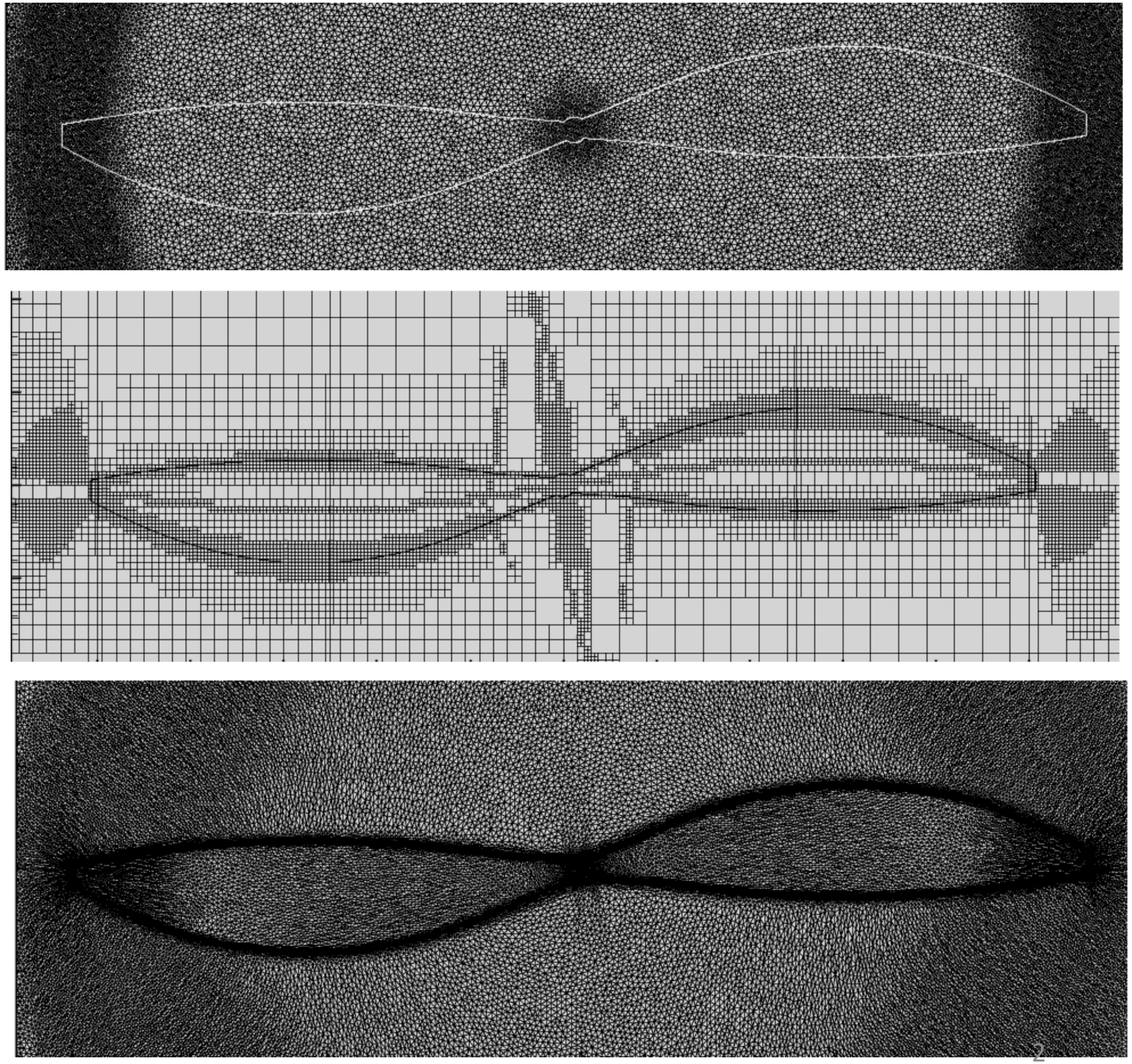
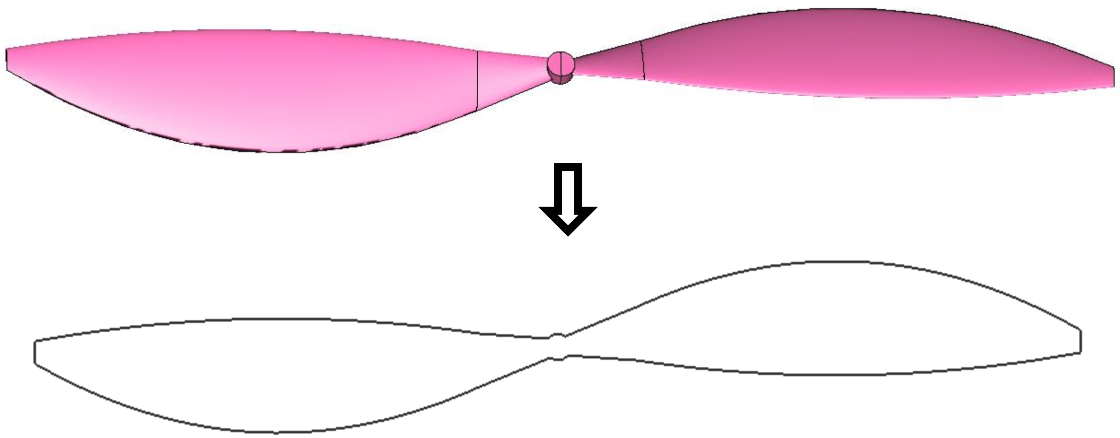
Main features of the technique

- Simply connected domain
- Geometry is defined by interpolation grid (level-set tree)
- Immersed boundary method (IBM) – Brinkman penalization
- The shape of the body is approximated using adaptation of r-type (nodes are redistributed while topology remains the same)
- Adaptation produces anisotropic cells



Statement of the problem



Projection of 3D geometry on z=0

Propeller* of size $R = 0.256\ m$ is rotating clockwise with $f = 3000\ rpm$

Upstream flow $U_0 = 10\ m/s$

*J. B. Brandt.(2005) “Small-scale propeller performance at low speeds”. Master thesis, University of Illinois at Urbana-Champaign.

Features of the adaptation technique

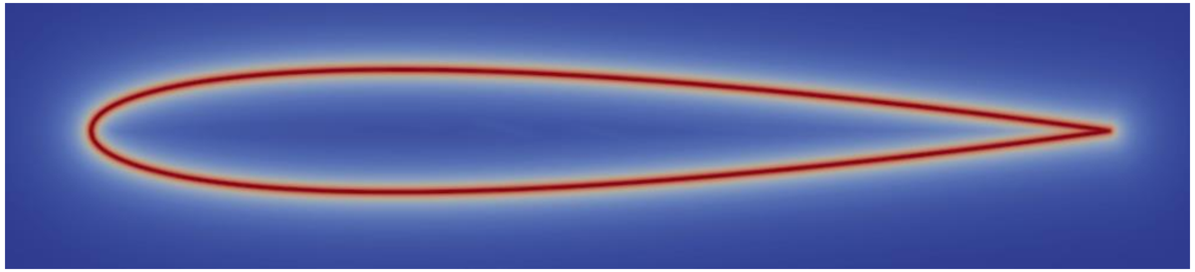
- Level-set function u(x,t) defines the solid body location and is close to signed distance function near the boundary
- Metric tensor G(x,t) is built upon u(x,t) as

$$G(x,t) = \sigma_1^2 I + (\sigma_2^2 - \sigma_1^2)\nabla_x u \nabla_x u^T \frac{1}{|\nabla_x u|^2} \xrightarrow{\sigma_2 = \sigma_1} G(x,t) = \sigma_1^2 I$$

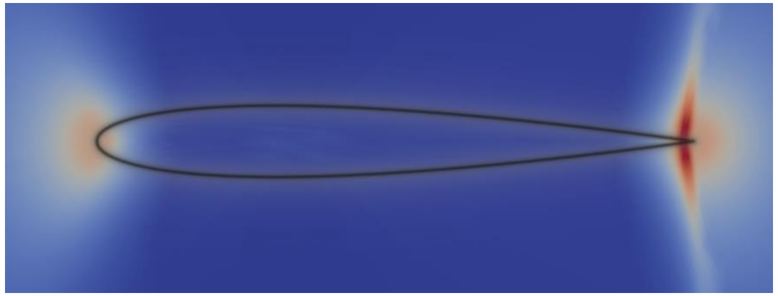
- On highly curved fragments of the boundary or near sharp vertices $\sigma_2 = \sigma_1$, otherwise $\sigma_2 = \sigma_1 / K$. K is user-defined anisotropic ratio.

$\sigma_1 = \sigma_{\text{normal}}(x,t)$ - mesh stretching in the normal direction

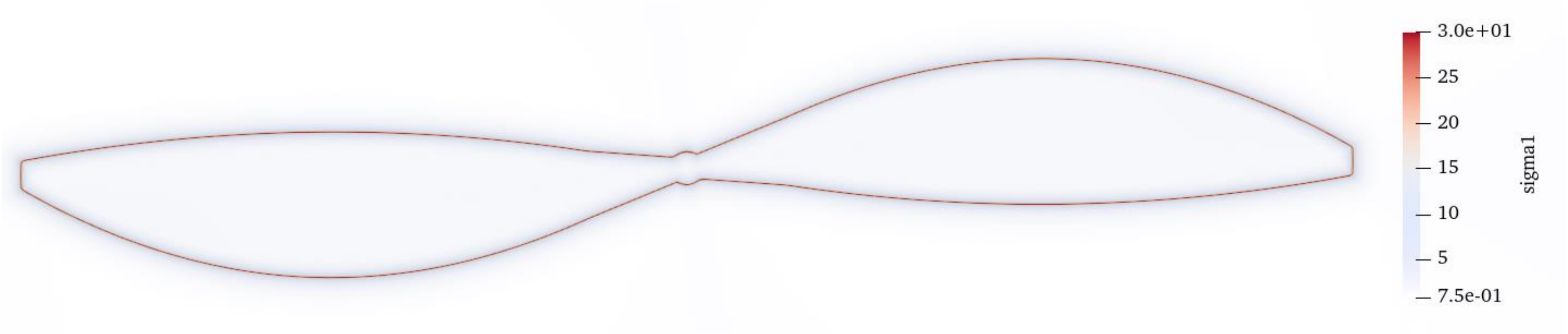
$\sigma_2 = \sigma_{\text{tangential}}(x,t)$ ($\sigma_{2,3}$ in 3D) - spatial distribution of the anisotropy

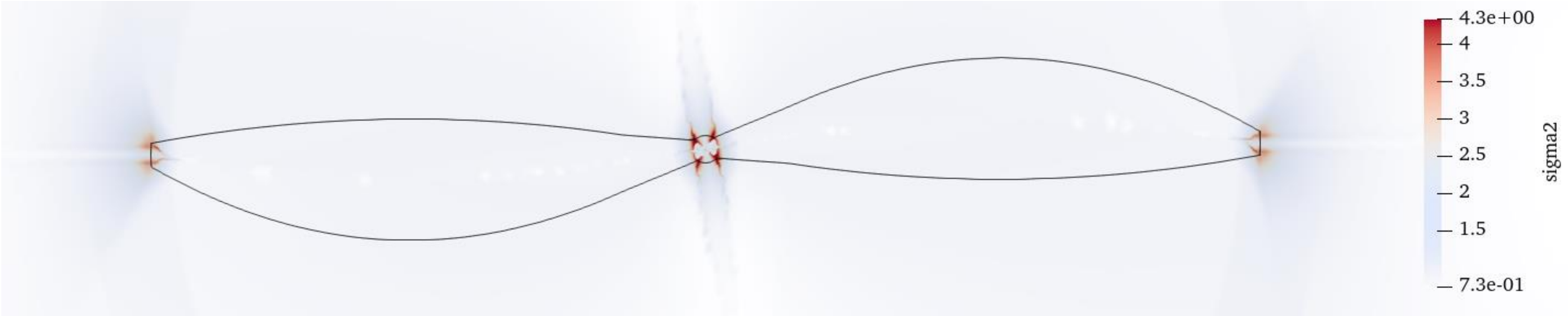


σ_1 distribution



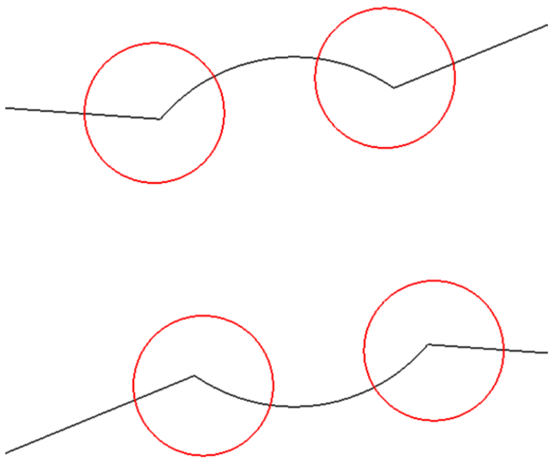
σ_2 distribution

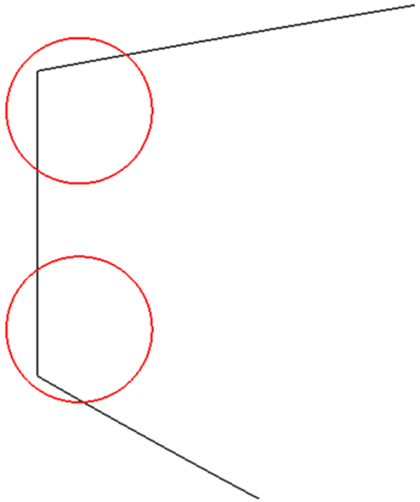

3.0e+01
25
20
15
10
5
7.5e-01
sigma1

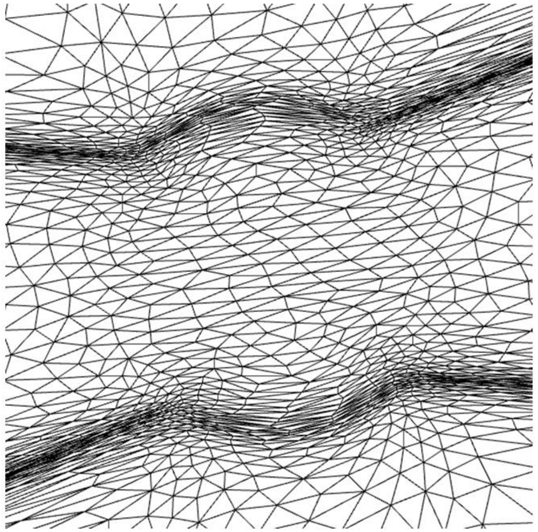

4.3e+00
4
3.5
3
2.5
2
1.5
7.3e-01
sigma2

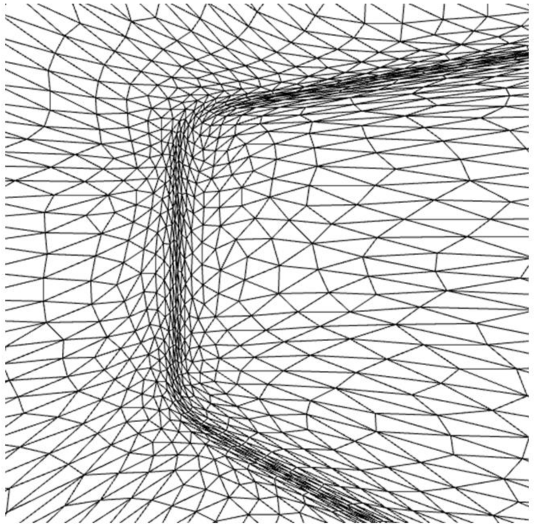

9.2e+01
80
60
40
20
1.1e-01
anisotropy

Adaptation for propeller projection

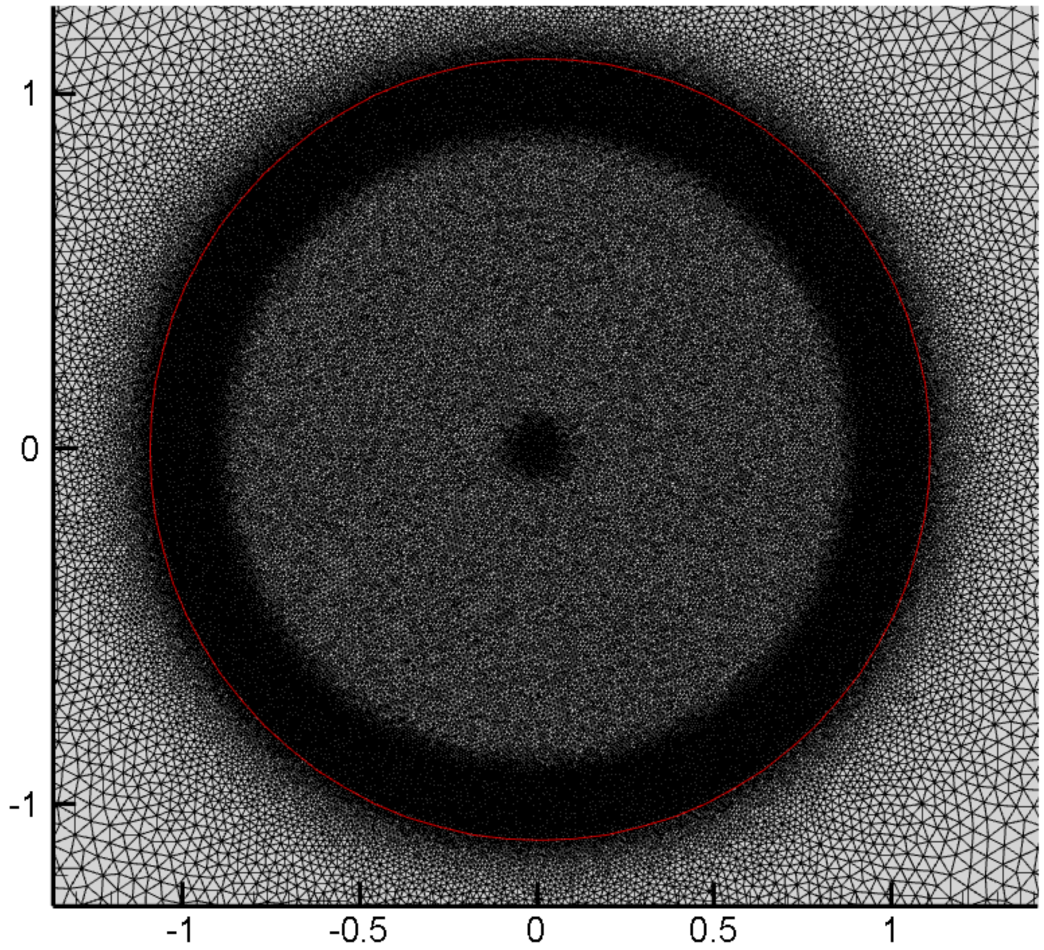




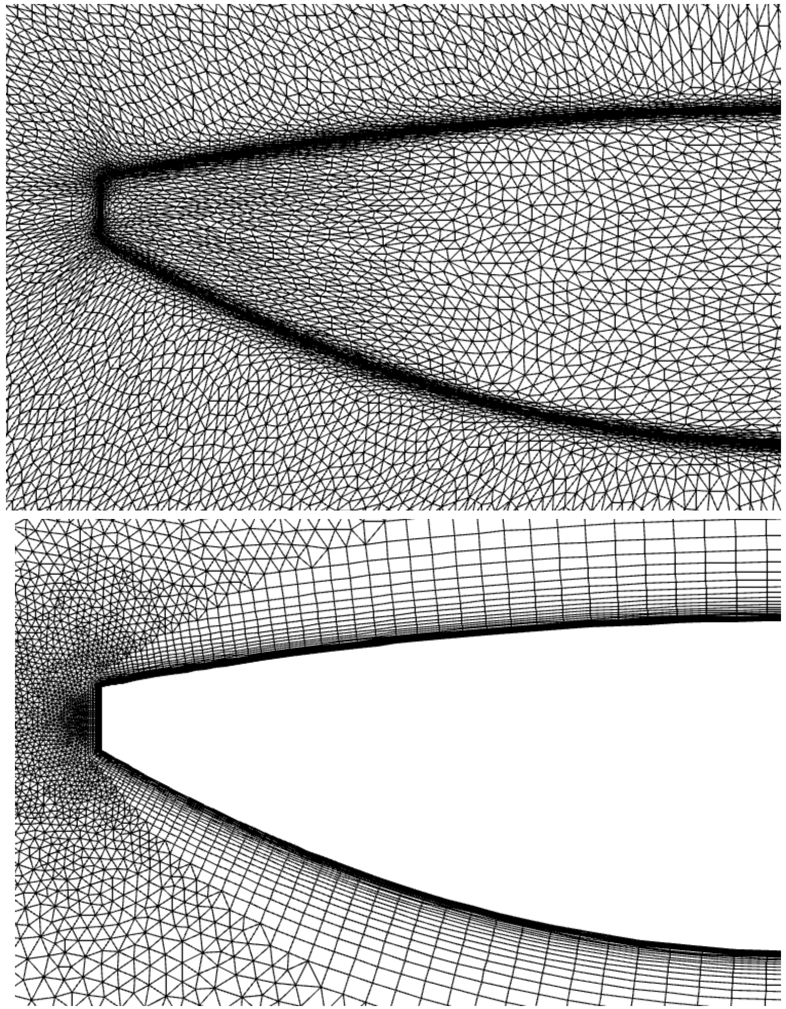




Adaptation for propeller projection

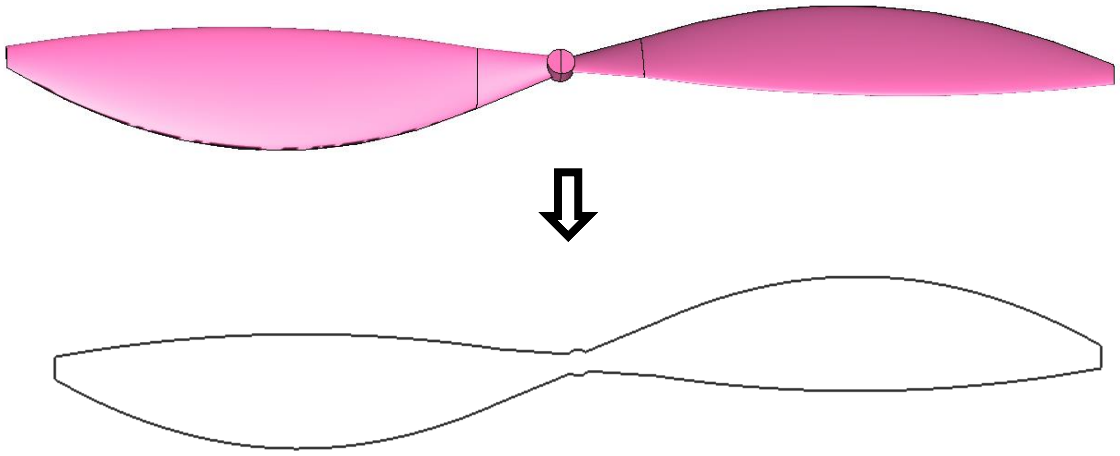


Starting mesh is prepared beforehand. Vertices outside red circle are not moving.



All further comparisons with be performed with use of body-fitted meshes (BFM)

Comparison: with the solution of RANS + SA in non-inertial system of coordinates associated with the propeller performed on body-fitted mesh



2D geometry

Additional problems:

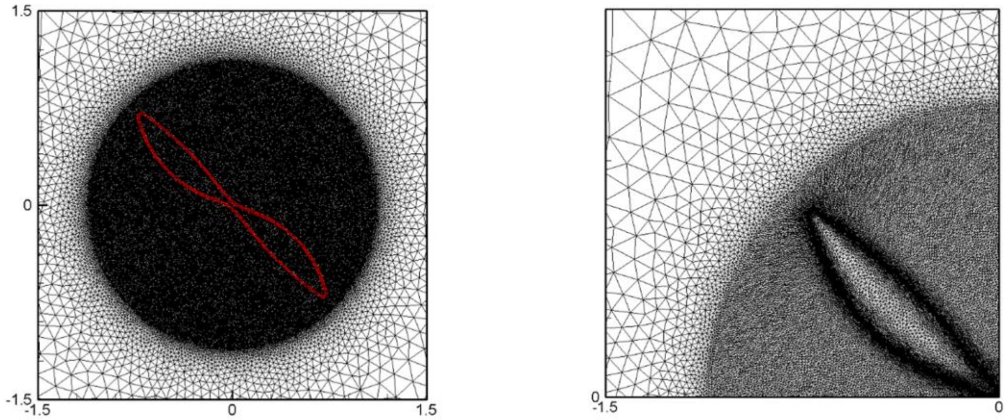
1. Propeller is fixed, upstream flow M=0.23
2. Propeller is fixed, upstream flow M=0.029
3. Propeller is rotating, no upstream flow M=0

Propeller of size $R = 0.256\ m$ is rotating clockwise with $f = 3000\ rpm$

Upstream flow $U_0 = 10\ m/s$

After normalization:

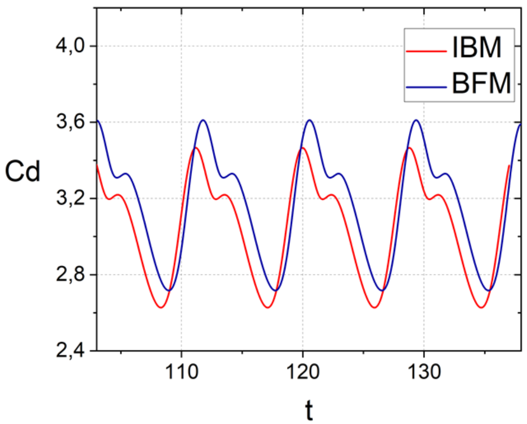
$\mathrm{Re} = 1.3 \cdot 10^6,\ M_{flow} = 0.029,\ M_{ref} = 0.23$

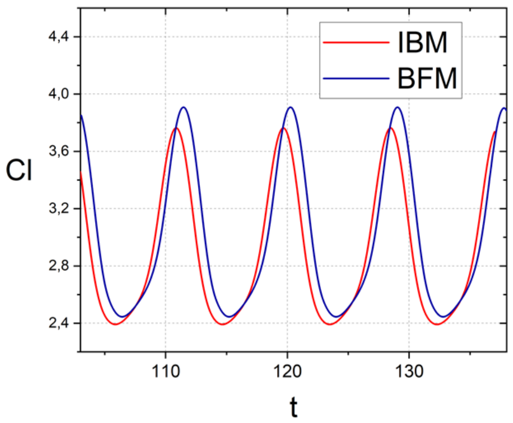


Fixed rotor

Results for single propeller

Problem 1:



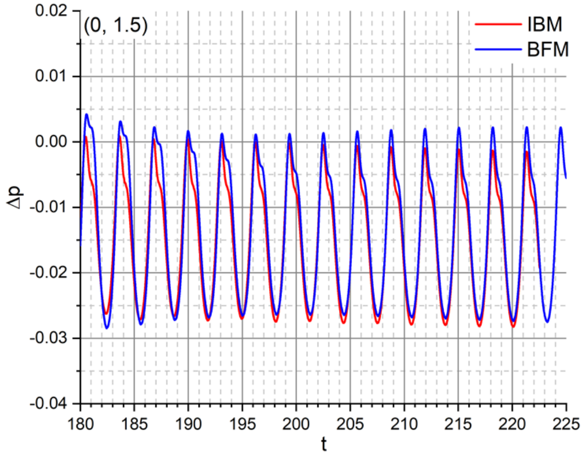


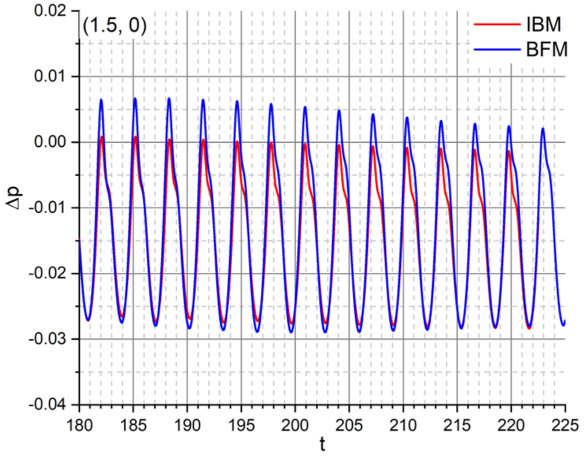
Problem 1,2: p, v, u are taken in (1.5, 0, 0)

		$\bar{C}_D$	$\bar{C}_L$	St
M = 0.23	IBM	3.063	2.925	0.114
	BFM	3.167	2.994	0.114
M = 0.029	IBM	0.054	0.050	0.012
	BFM	0.058	0.053	0.009

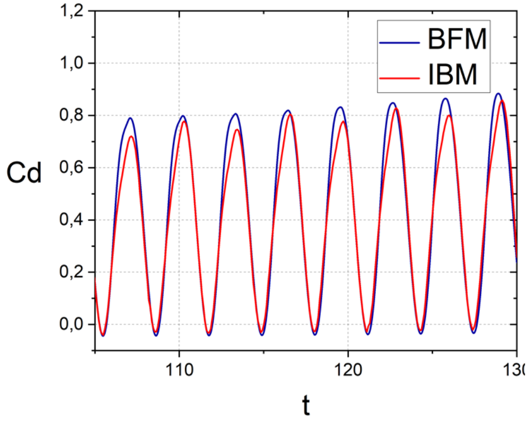
		$\bar{p}$	$\bar{u}$	$\bar{v}$
M = 0.23	IBM	11.91	-0.290	-0.0903
	BFM	11.92	-0.307	-0.0995
M = 0.029	IBM	13.02	-0.023	-0.0158
	BFM	13.02	-0.026	-0.0113

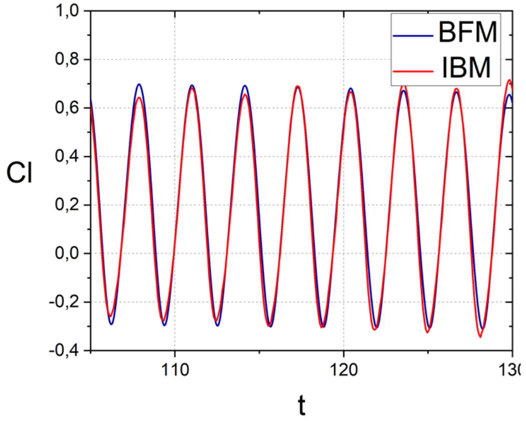
Problem 3:

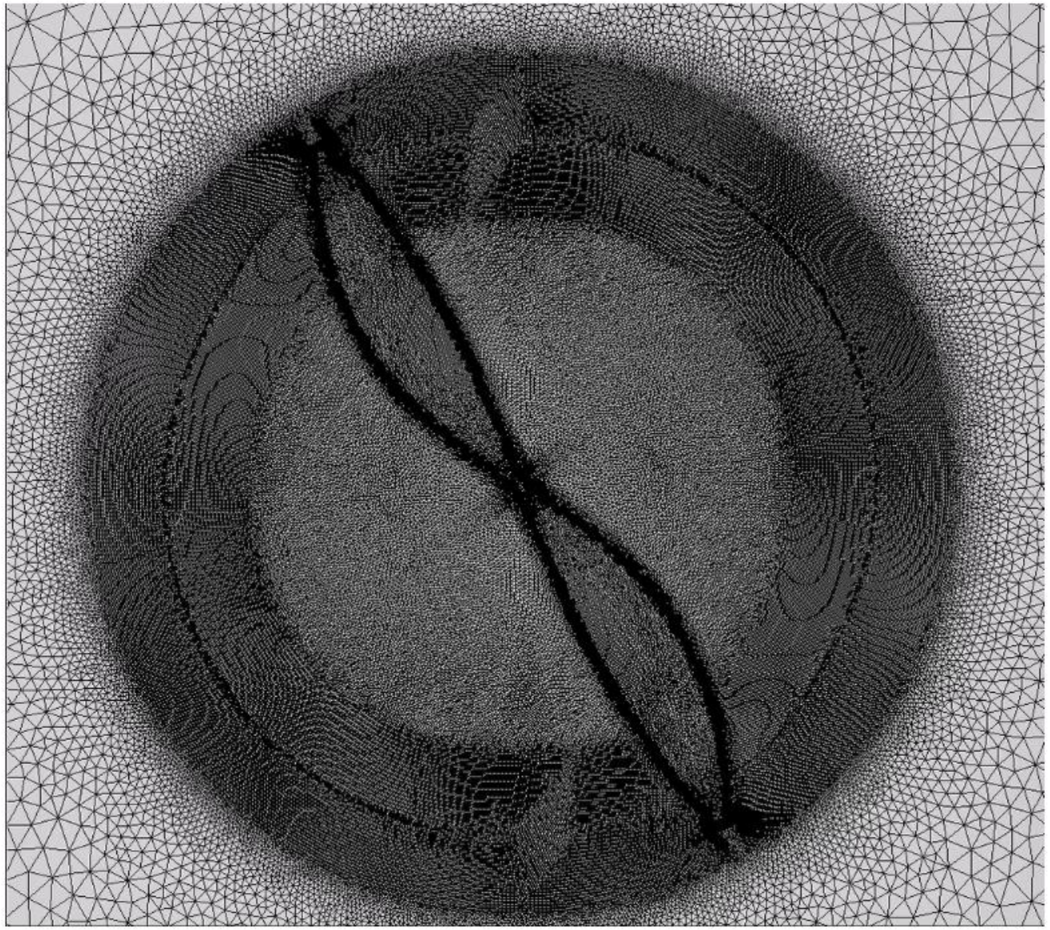


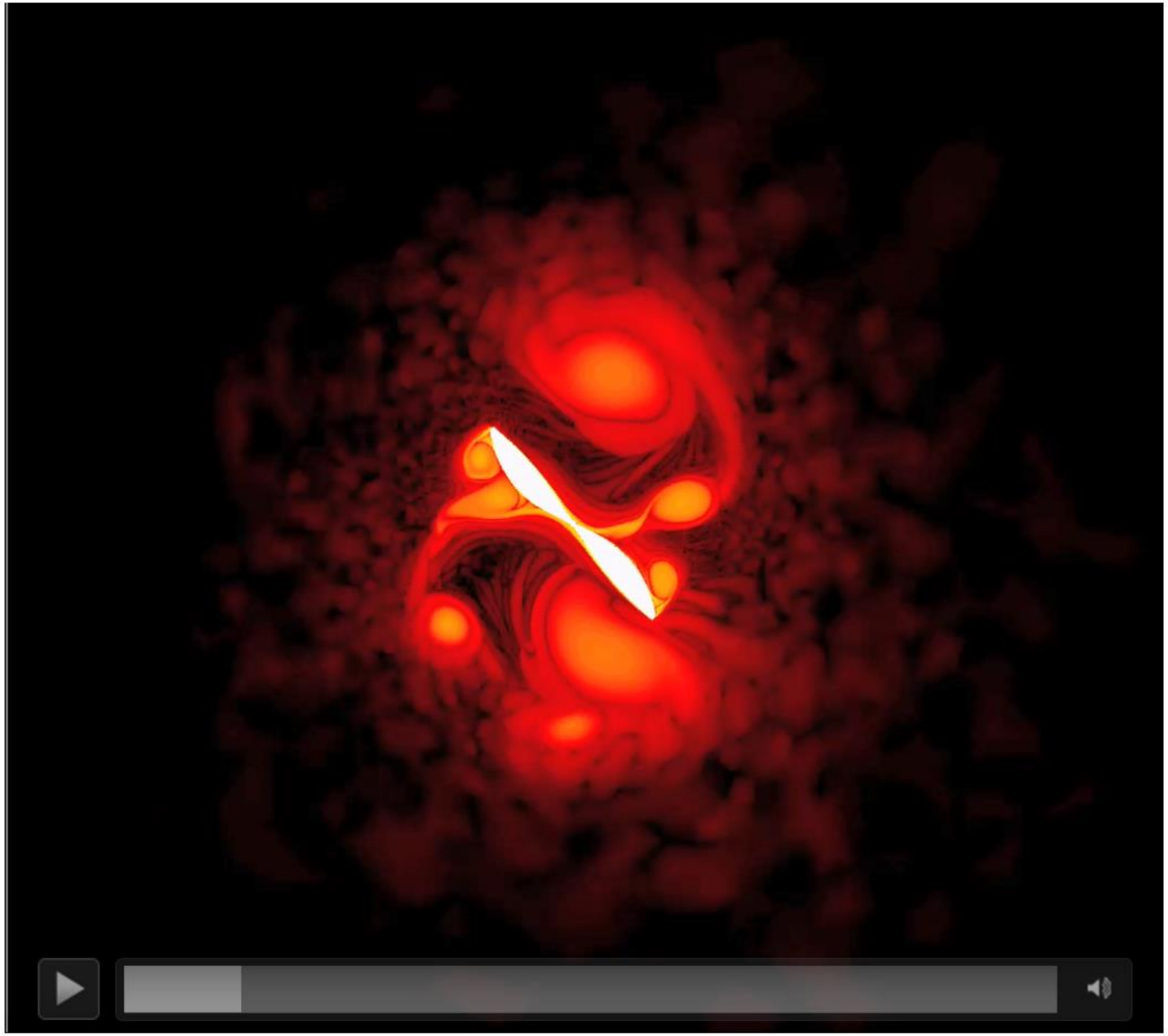


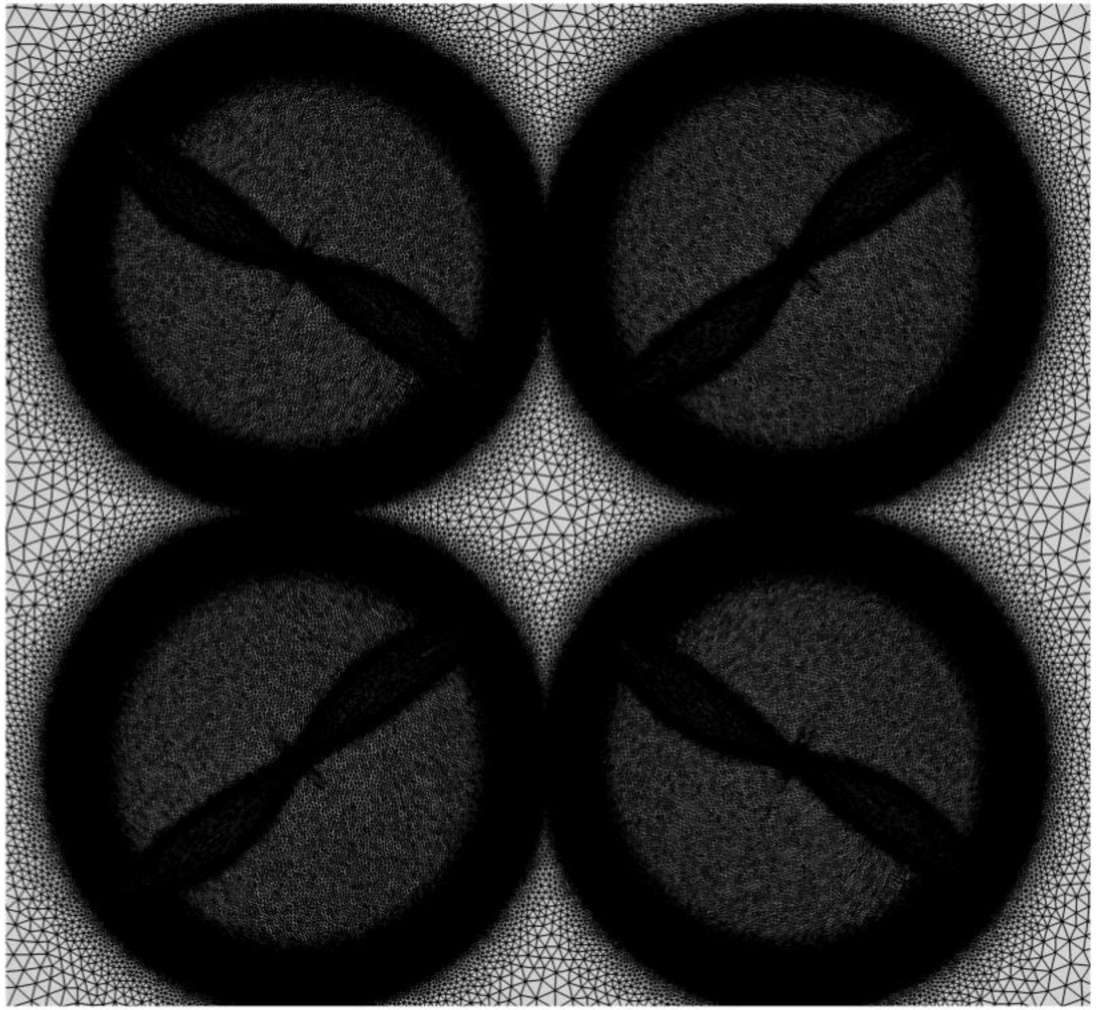
For original formulation:

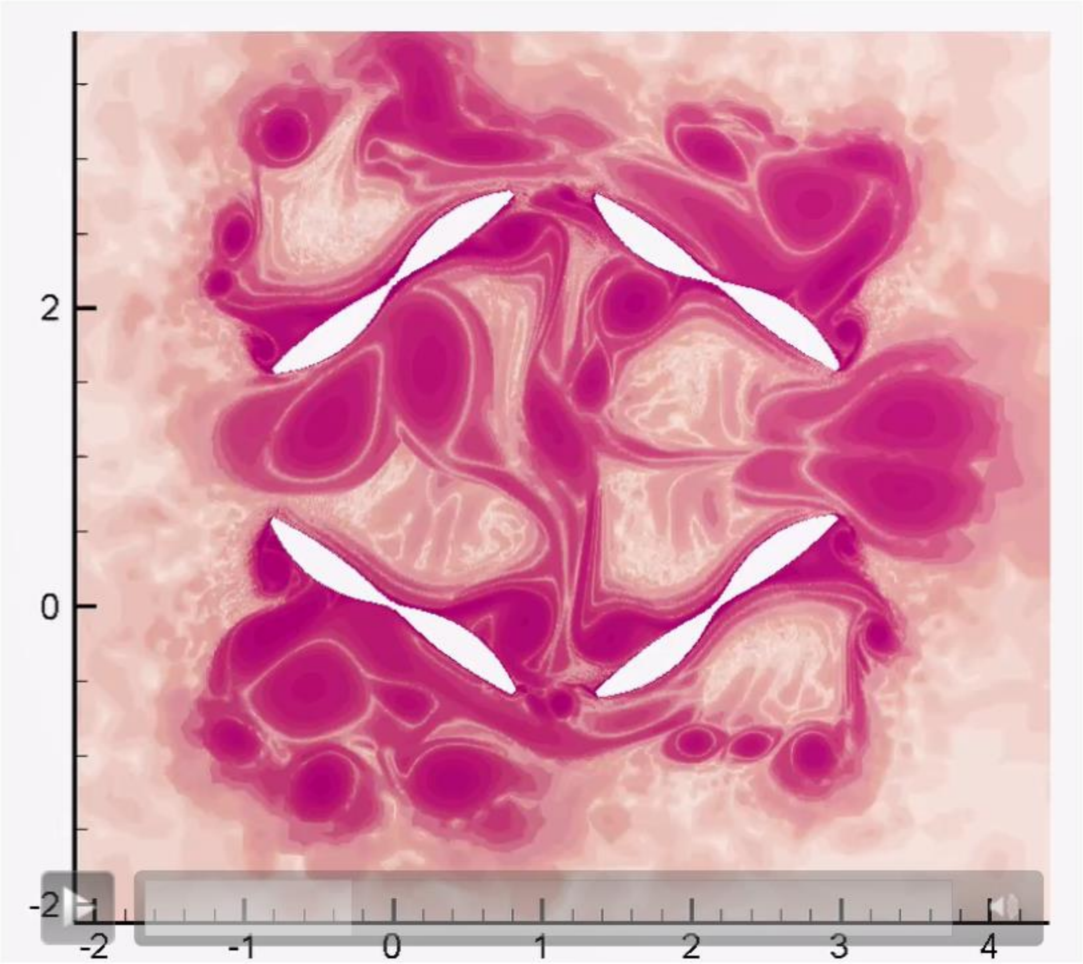




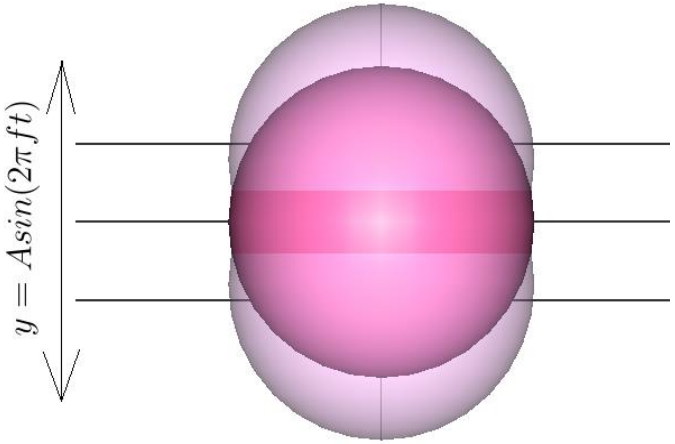




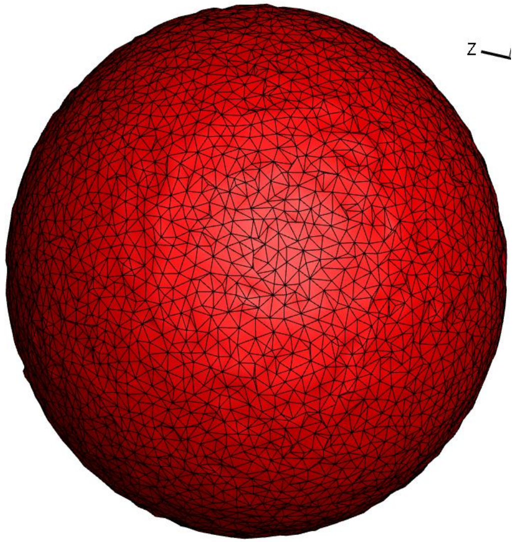



2
0
-2
-2
-1
0
1
2
3
4

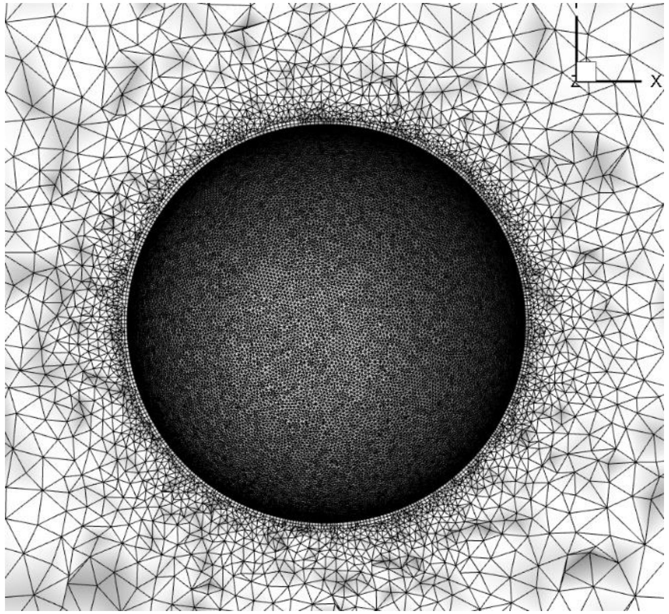
Testing for 3D case



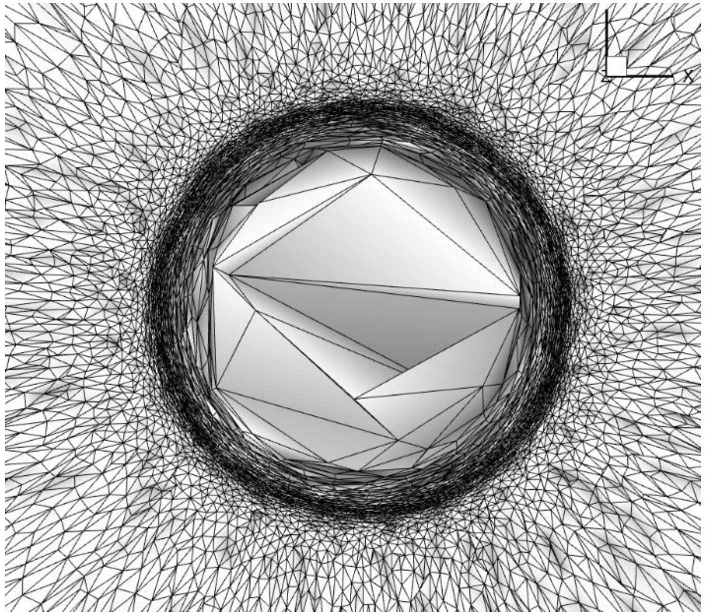
Sphere of size D = 1 is making forced harmonic movement along Oy with f=0.15,
A=0.2
Re=318.8



Solid domain

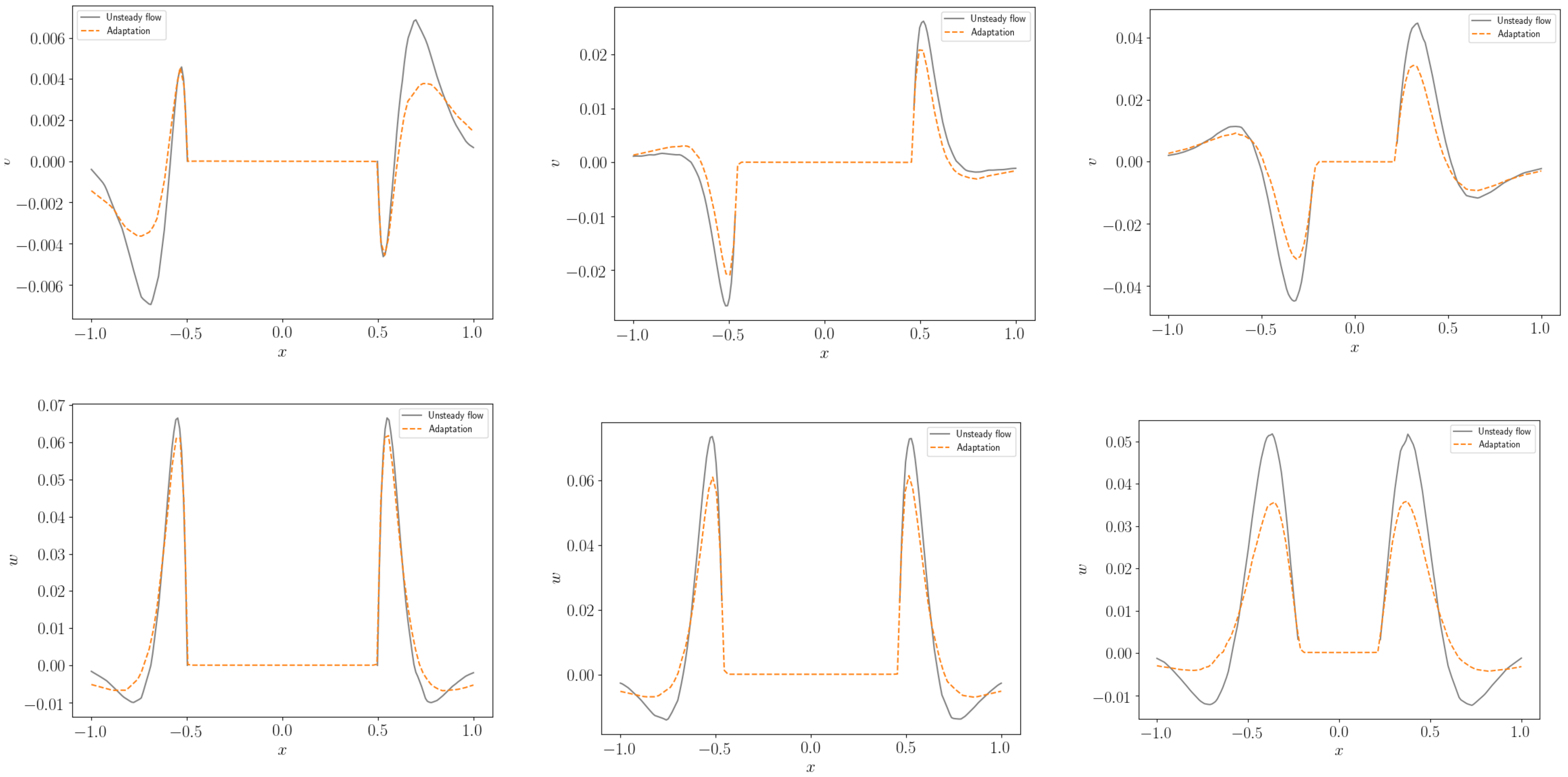


Body-fitted mesh

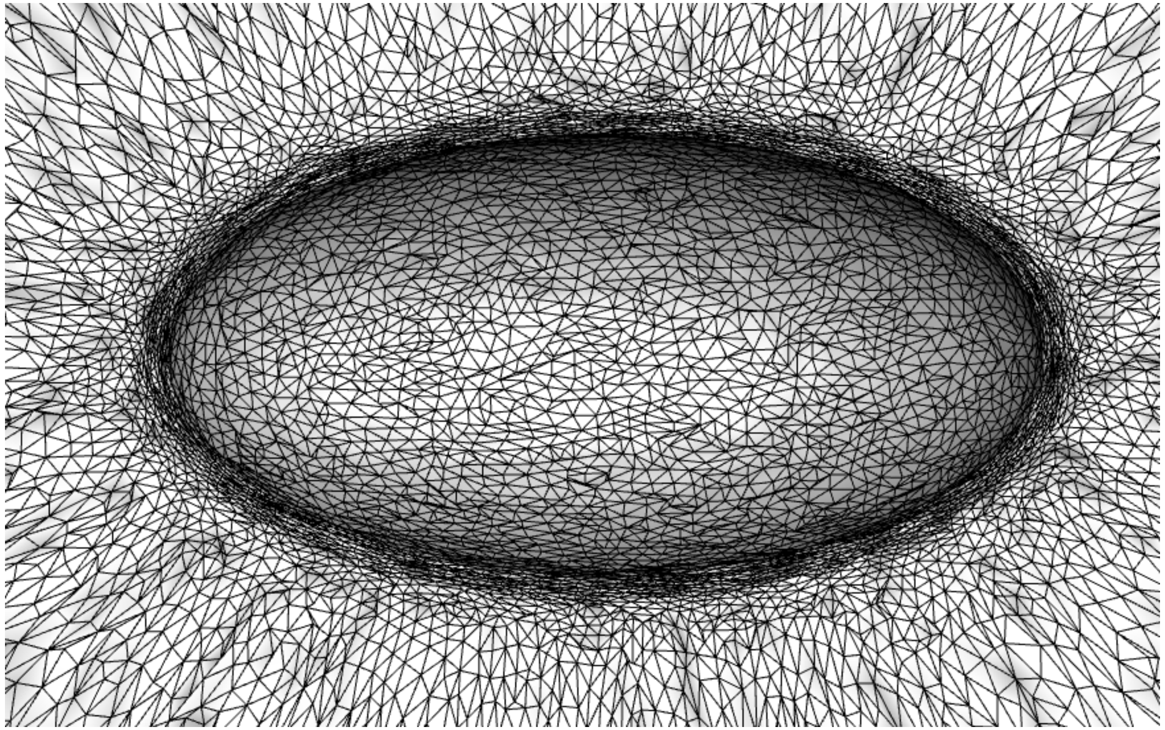


Adapted mesh

Testing for 3D case: comparison in profiles y={-0.25, 0, 0.25}; x=0; -1<z<1



Adaptation for ellipsoid (solid part is blanked)



Problems to solve

- automatic control of anisotropic adaptation along complicated shapes
- complicated 3D shapes
- efficiency improvements