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

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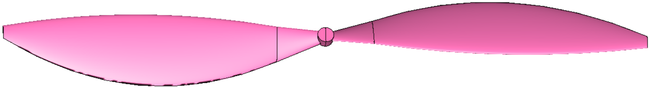
Outline

- Statement of the problem
- Mathematical model
- Numerical method
- Adaptation algorithm
- Results
- Problems to solve

Problem

- Original formulation



$R = 0.254\ m$
$f = 3000\ rpm$
upstream flow $U_0 = 10\ m/s$

- 2D formulation

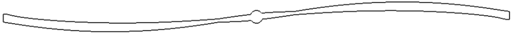


Figure 1: Section of original geometry by plane z=0

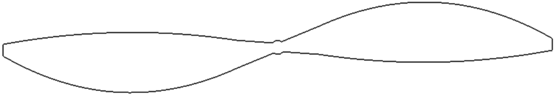
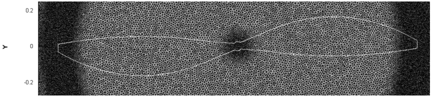


Figure 2: Projection to the plane z=0

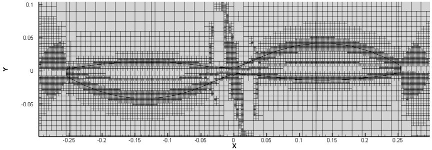
Outline of the technique

Main features of our technique:

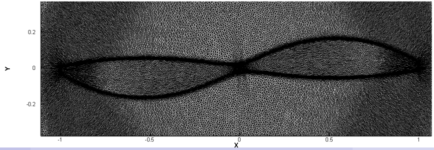
- Simply connected domain thanks to immersed boundary method (IBM)



- Geometry if defined by interpolation grid (level-set tree)



- IBM - Brinkman penalization
- The shape of the body is approximated using adaptation of r-type (nodes are redistibuted while topology remains the same)



Mathematical model

The mathematical model for simulating viscous compressible flow over moving obstacles is based on the system of Reynolds-Averaged Navier-Stokes equations with Spalart–Allmaras turbulence model.

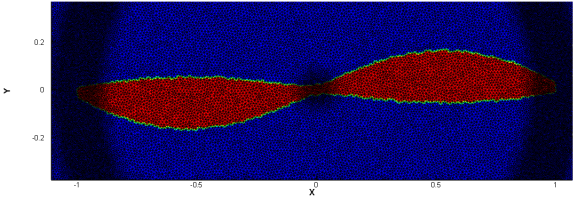


Figure 3: Nodes are categorized as solid or fluid points.

The no-slip condition is imposed between solid Ω_B and fluid Ω_f:

$$\boldsymbol{u}\big|_{\partial\Omega_B} = \boldsymbol{V}, \tag{1}$$

where $\boldsymbol{V}$ - body velocity, $\boldsymbol{u}$ - fluid velocity. In nodes inside the solid extra source terms are added to the equations.

Numerical method

Research code NOISEtte for simulation of unsteady aerodynamics and aeroacoustics problems.

- Edge-Based Reconstruction scheme (EBR)
- Time integration is performed using an implicit second-order scheme
- At each time step Newtonian iteration is performed: linearized system of equations is solved by biconjugate gradient stabilized method.

Adaptation algorithm

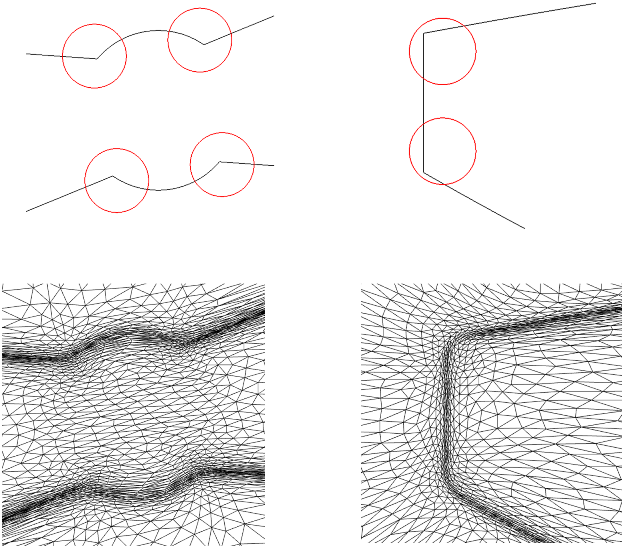
Main features of adaptation algorithm:

- Adaptation uses variational approach
- Level-set function $u(x, t)$ defines the solid body and is close to signed distance function near the boundary of the domain
- Metric tensor $G(x, t)$ is built upon $u(x, t)$ as

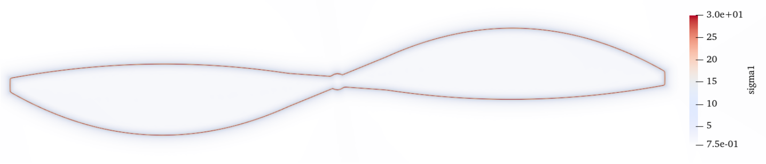
$$G(x, t) = \sigma_1^2 I + (\sigma_2^2 - \sigma_1^2)\nabla_x u \nabla_x u^T \frac{1}{|\nabla_x u|^2}, \tag{2}$$

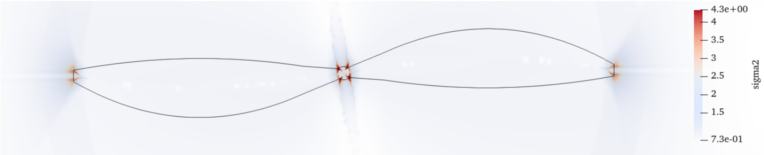
- $\sigma_1 = \sigma_{\text{normal}}(x, t)$ - mesh stretching in the normal direction
  $\sigma_2 = \sigma_{\text{tangential}}(x, t)$ ($\sigma_{2,3}$ in 3D) - spatial distribution of the anisotropy.

Adaptation algorithm



Adaptation algorithm





Adaptation algorithm

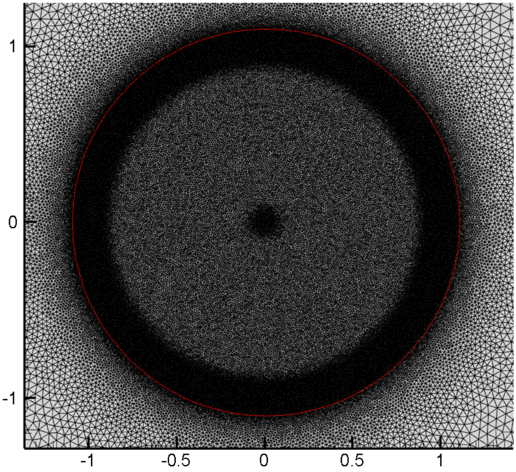
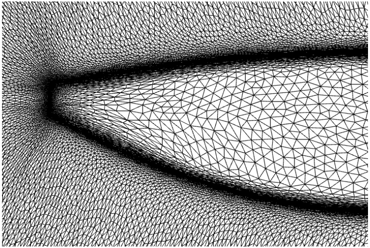


Figure 4: Original mesh. Mesh outside the red circle remains unchanged

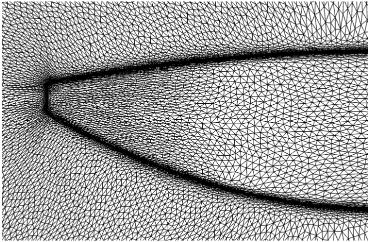
Adaptation algorithm

Stationary adaptation (a) and mesh after 10 periods (b).

(a)



(b)



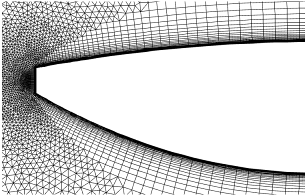


Figure 6: Body-fitted mesh.

Results. Stationary propeller

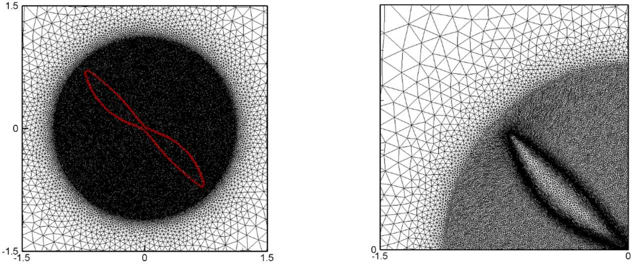
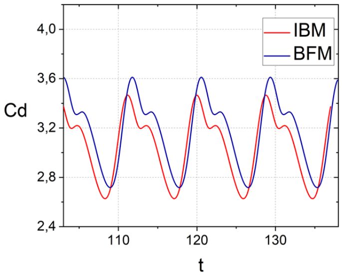


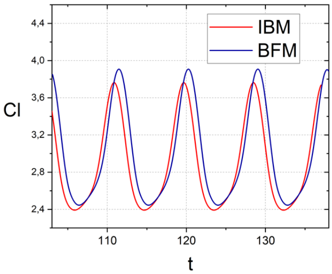
Figure 7: Starting mesh

Problem 1. Propeller is fixed.
Upstream flow $M = M_{BL} = U_{BL}/(\sqrt{\gamma R T_0}) = 0.23.$
Problem 2. Propeller is fixed.
Upstream flow $M = M_0 = U_0/(\sqrt{\gamma R T_0}) = 0.029.$
Problem 3. Propeller is rotating. Upstream flow $M = 0.$
$Re = 1.3 \cdot 10^6$

Results

- Problem 1

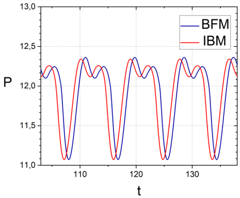




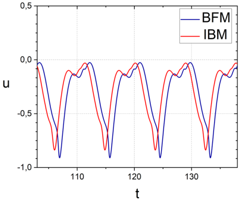
Results. Stationary propeller

Comparison is taken in points (1.5, 0) and (0, 1.5).

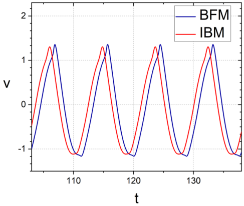
(a)



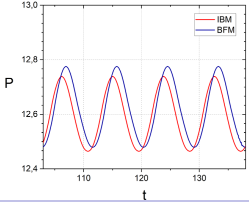
(b)



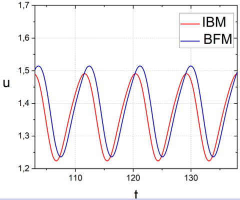
(c)



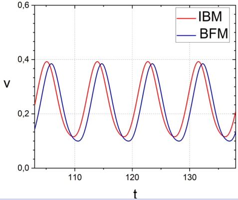
(a)



(b)



(c)



Results

		$\overline{C}_D$	$\overline{C}_L$	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

In point (1.5, 0):

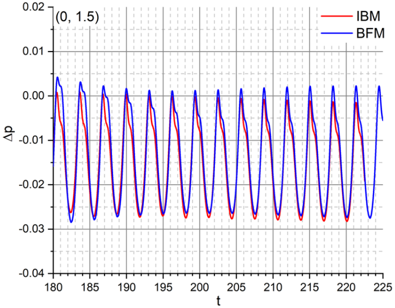
		$\overline{p}$	$\overline{u}$	$\overline{v}$
M = 0.23	IBM	11.91	-0.290	-0.0903
	BFM	11.92	-0.307	-0.0995
M = 0.029	IBM	13.02	-0.023	-0.0158
	BFM	13.02	-0.026	-0.0113

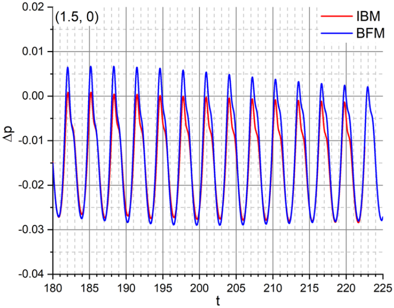
In point (0, 1.5):

		$\overline{p}$	$\overline{u}$	$\overline{v}$
M = 0.23	IBM	12.59	1.364	0.239
	BFM	12.62	1.382	0.225
M = 0.029	IBM	13.04	0.167	0.031
	BFM	13.04	0.165	0.025

Results

- Problem 3





Results. Rotating propeller

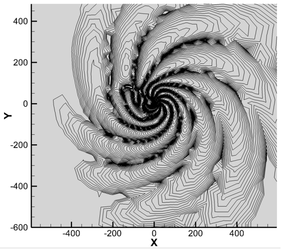
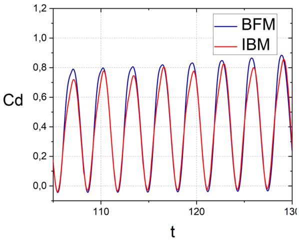
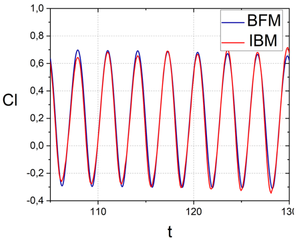


Figure 10: Vorticity





Problems to solve

- section instead of projection
- efficiency improvements. Now adaptation takes $\sim 20\%$ of the time step
- 4 rotating propellers
- automatic control of anisotropic adaptation along complicated shapes
- 3D formulation (2021)