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 redistributed 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 \( \Omega_B \) and fluid \( \Omega_f \):

\[ u \big|_{\partial \Omega_B} = V, \]  

where \( V \) - body velocity, \( u \) - 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.
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

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

- $\sigma_1 = \sigma_{\text{normal}}(x, t)$ - 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).

Figure 6: Body-fitted mesh.
Results. Stationary propeller

Problem 1. Propeller is fixed.
Upstream flow \( M = M_{BL} = U_{BL}/(\sqrt{\gamma RT_0}) = 0.23. \)

Problem 2. Propeller is fixed.
Upstream flow \( M = M_0 = U_0/(\sqrt{\gamma RT_0}) = 0.029. \)

Problem 3. Propeller is rotating. Upstream flow \( M = 0. \)
\( Re = 1.3 \cdot 10^6 \)

Figure 7: Starting mesh
Results

- Problem 1

![Graph showing Cd and Cl over time for IBM and BFM models.](image-url)
Results. Stationary propeller

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

(a)  

(b)  

(c)  

(a)  

(b)  

(c)  

(a)  

(b)  

(c)
## Results

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In point (1.5, 0):

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In point (0, 1.5):

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Results

Problem 3
Results. Rotating propeller

Figure 10: Vorticity

Figure 11: Time evolution of $C_d$ and $C_l$
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)