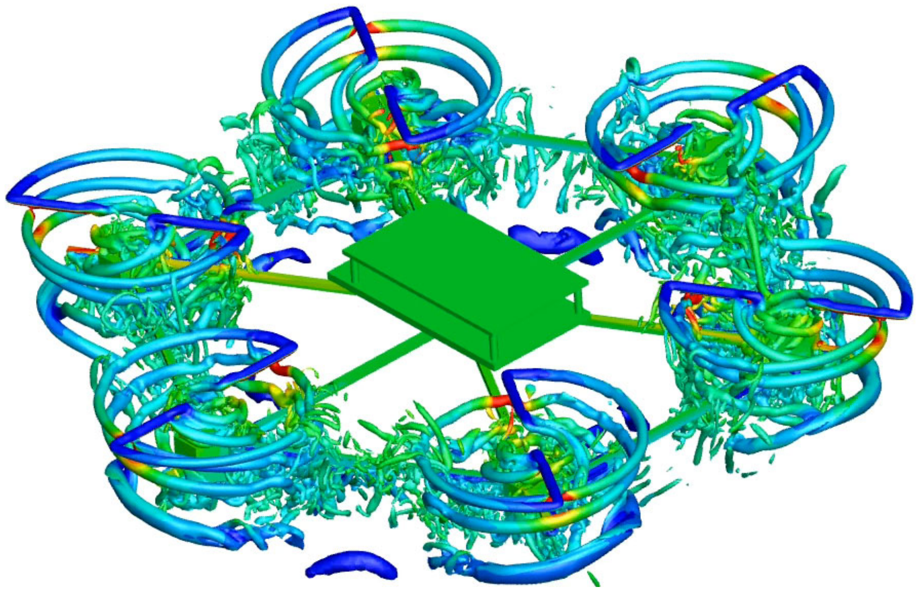
19th, March, 2025
2024年度将来回転翼機研究会／回転翼解析技術交流会

ブレード要素理論とアクチュエータラインモデルの組み合わせによるマルチコプターローターの3D流れ解析手法の開発



◯ 今村太郎, 川﨑達輝, 藤原啓明, 玉置義治, 森田直人（東大）
大塚光（金沢大学）, 山田健翔, 加藤裕之, 上野真（JAXA）

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- 背景
- 目的
- 数値解析手法
  - ✓Hierarchical Cartesian grid based flow solver, UTCart
  - ✓プロペラ解析手法
    - ➢Actuator Line Model
    - ➢Actuator Disk Model and UTCart on rotational frame
- 解析事例
  - ✓Single rotating blade simulation
  - ✓Hexacoptor simulation
- まとめ

Background: Design of rotorcraft

- New aircraft (UAV, AAM)
  - ✓Multiple rotors
  - ✓Wing, fuselage, empennage

} Aerodynamic interaction

CFD tools for aerodynamic design and certification

[1]

[2]

[3]

[1] DJI Mavic 3 Pro
[2] Boeing wisk
[3] CityAirbus

Background: Cost estimation for CFD

- UAV simulation (Direct approach)
  - ✓ Min. spatial scale: $O(10^{-6} \sim 10^{-5})$[m] (Turbulent scale)
  - ✓ Max. velocity scale: $O(10^{2})$[m] (Speed of sound)

    ⇨ Min. time scale: $O(10^{-9} \sim 10^{-8})$[sec]

  - ✓ Revolution per minute: $O(10^{3} \sim 10^{4})$[rpm]

    ⇨ Rotation period: $O(10^{-3} \sim 10^{-2})$[sec]

  - ✓ Time steps per period : $O(10^{6})$[step]

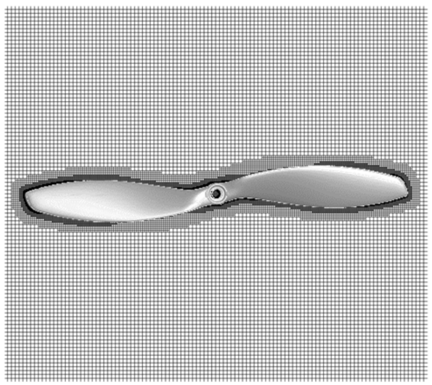
    ⇨ Total computational step $O(10^{7})$[step] or more
    $O(10 \sim 10^{2})$ rotations needed for aerodynamic interaction analysis

Solution:
Avoid resolving turbulent scales & rotor directly through modeling

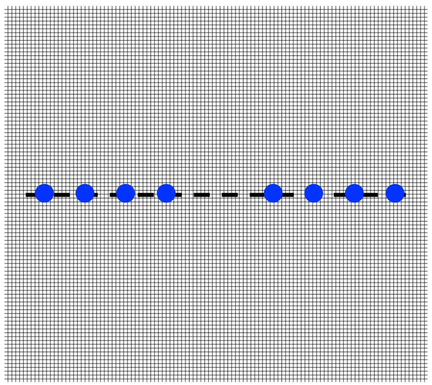
Background: CFD for Rotor

High-Cost & High-Fidelity | Mid-Cost & Mid-Fidelity | Low-Cost & Low-Fidelity

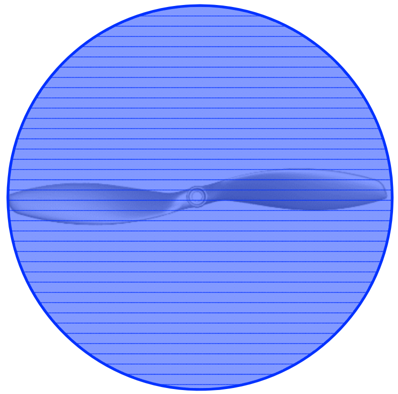
Direct Approach (Moving grid)
- ✓ Fully resolved
- ✓ Rotating grid (rotor) +Background grid (fuselage)
- ✓ Fine grid



Actuator Line Model (ALM) [1]
- ✓ Model the time-varying rotor-fluid interactions
- ✓ Background grid only
- ✓ Modest grid



Actuator Disk Model (ADM)
- ✓ Model the time-averaged rotor-fluid interaction
- ✓ Background grid only
- ✓ Modest grid

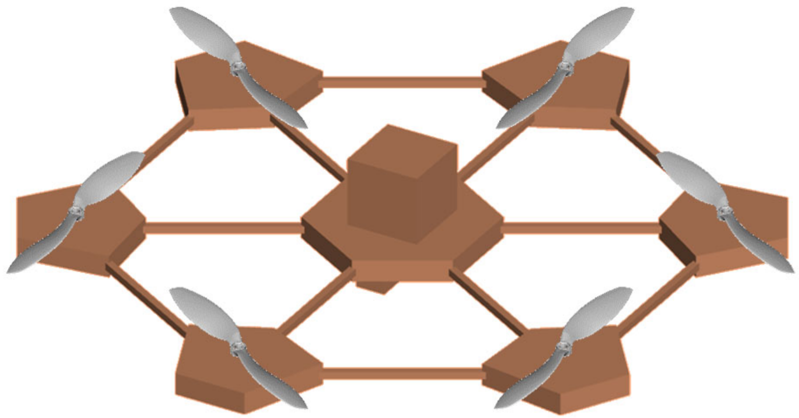


[1] Sørensen, J. N., & Shen, W. Z. (2002). Journal of Fluids Engineering

目的

- 圧縮性流体解析ソルバー UTCart に、アクチュエータラインモデル（ALM）を実装し、時間変化するローター-流体相互作用および空力相互作用（ローター-機体）を評価
- 単一ローターおよびヘキサコプターのシミュレーションを通じ、ALMの性能を明確にするため、後流特性と計算コストを評価

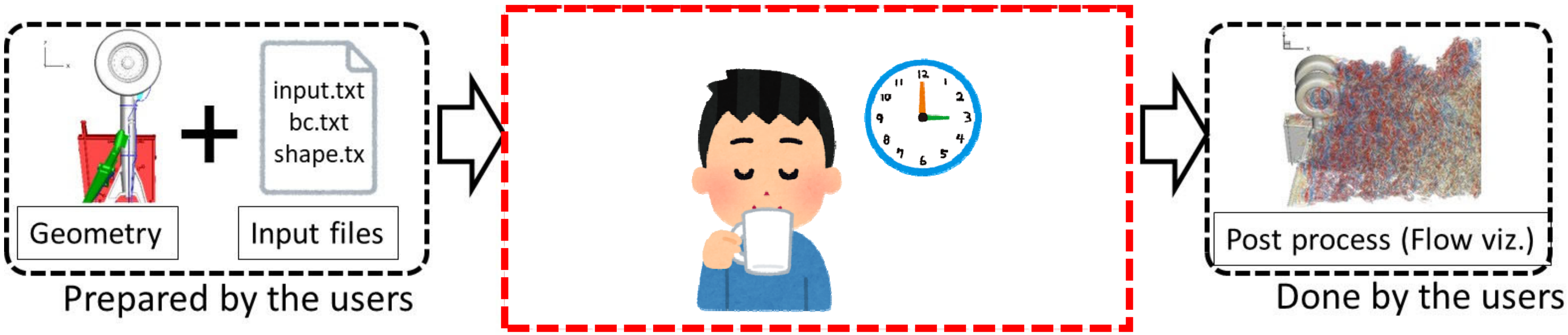
Single rotor simulation



Hexacoptor simulation

Methods: UTCart

- The University of Tokyo Cartesian-Grid-Based Automatic Flow Solver
  - ✓２次元版／３次元版
  - ✓自動格子生成機能：CADデータから数値解析結果をシームレスに得ることができ、航空機の概念設計や空力最適化において有用
  - ✓圧縮性流体解析：埋め込み境界法を採用し、物体適合格子を用いる従来の方法に近い計算精度を実現
  - ✓ユーザーフレンドリー：入力形状（2D:点列、3D：STL）、解析条件設定ファイル（3つ）が準備できれば、コマンド1つで解析可能
  - ✓複数のOS環境に対応：Windows/Mac OS/ Linux…

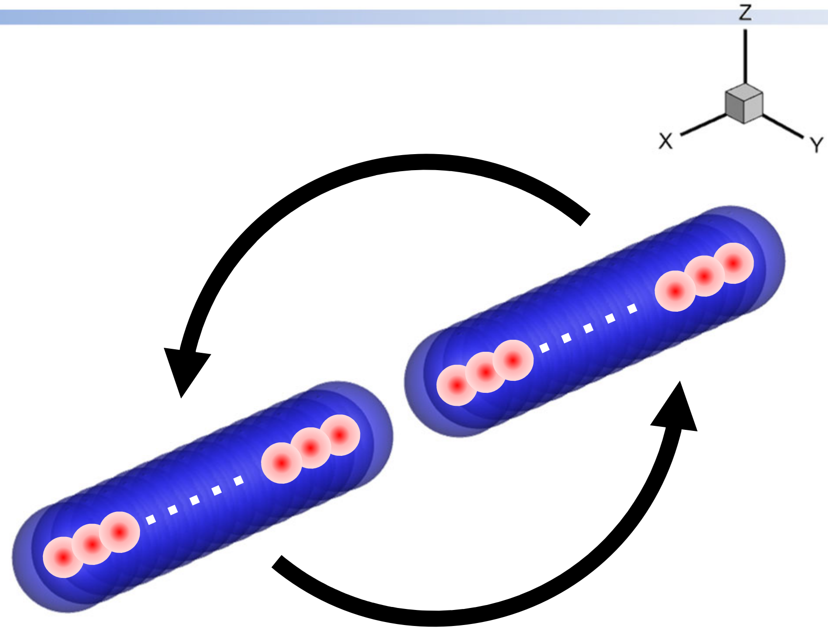


Methods: Governing equations of ALM

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + F_{S,i}$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial \rho H u_j}{\partial x_j} = \frac{\partial u_i \tau_{ij}}{\partial x_j} - \frac{\partial q_j}{\partial x_j} + E_S$$



$$\boldsymbol{F}_S = \sum_{n=1}^{N_P} \left(-\boldsymbol{f}(r_n)\Delta R\right) g_n(\boldsymbol{x})$$

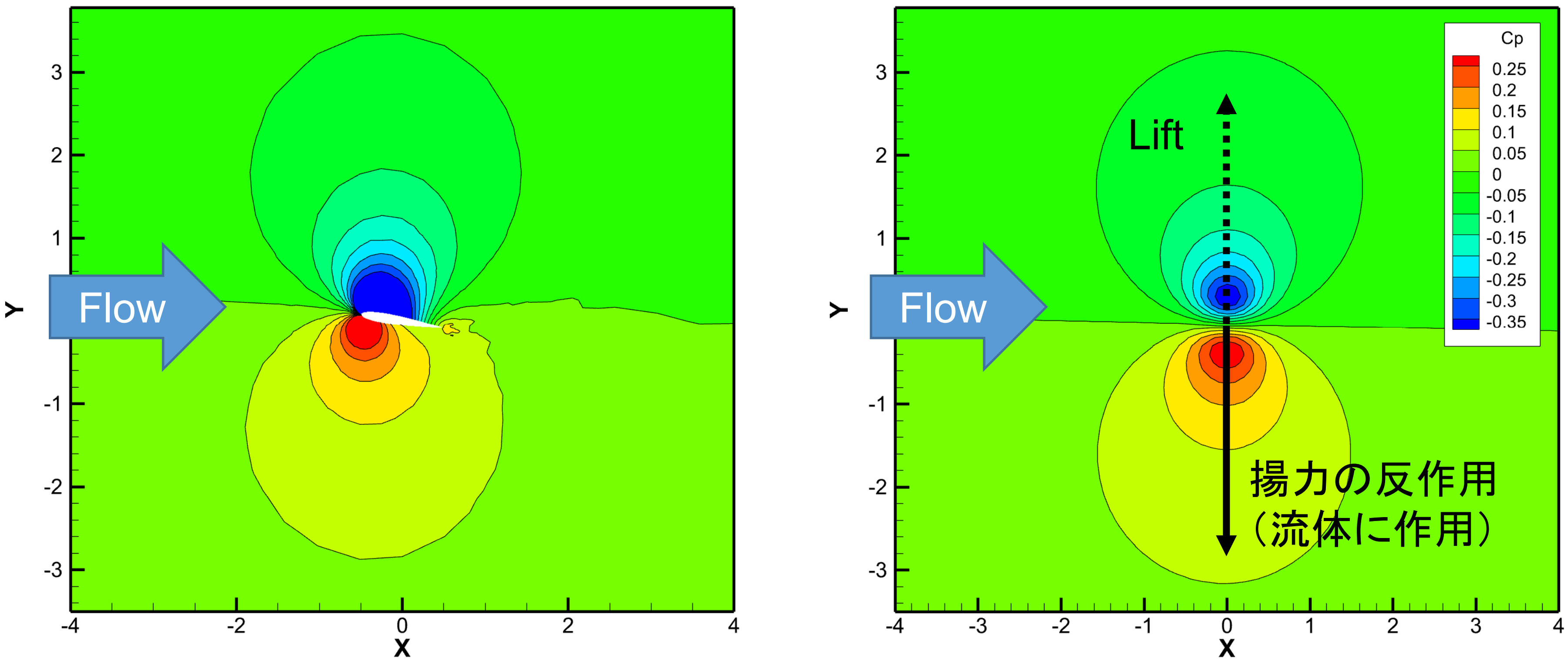
$$E_S = \sum_{n=1}^{N_P} \left(-\boldsymbol{f}(r_n)\Delta R\right) \cdot (\boldsymbol{\Omega} \times \boldsymbol{r}_n) g_n(\boldsymbol{x})$$

$$g_n(\boldsymbol{x}) = \frac{1}{\left(\sqrt{2\pi\sigma^2}\right)^3} \exp\left(-\frac{|\boldsymbol{x} - \boldsymbol{\mu}_n|^2}{2\sigma^2}\right)$$

- ✓ N_P : the number of point sources
- ✓ $(-\boldsymbol{f}(r_n)\Delta R)$: force for a point source
- ✓ $(\boldsymbol{\Omega} \times \boldsymbol{r}_n)$: velocity for a point source
- ✓ $g_n(\boldsymbol{x})$: 3D Gaussian kernel
  - ➢ $\boldsymbol{\mu}_n(t)$: location of point sources
  - ➢ $\sigma = 0.2c_{75}$: standard deviation

【補足】

- 外力項により翼型周りの流れを模擬



Airfoil simulation
RANS, Re=3×10^6, Freestream Mach=0.2, AoA=9.6deg

Point Source Model
(The same force applied)

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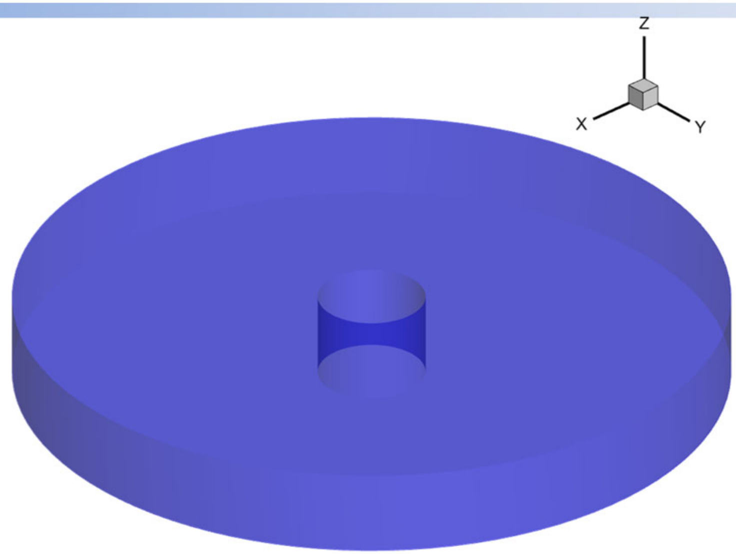
Methods: Governing equations of ADM

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + F_{S,i}$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial \rho H u_j}{\partial x_j} = \frac{\partial u_i \tau_{ij}}{\partial x_j} - \frac{\partial q_j}{\partial x_j} + E_S$$



$$\boldsymbol{F}_S = N_b \frac{-\boldsymbol{f}(r)}{2\pi r} g(z)$$

$$E_S = N_b \frac{-\boldsymbol{f}(r) \cdot (\boldsymbol{\Omega} \times \boldsymbol{r})}{2\pi r} g(z)$$

$$g(z) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{|z - z_{\mathrm{rotor}}|^2}{2\sigma^2}\right)$$

- ✓ N_b : the number of blades
- ✓ $-N_b \boldsymbol{f}(r)/(2\pi r)$: force per unit area
- ✓ $-N_b \boldsymbol{f}(r) \cdot (\boldsymbol{\Omega} \times \boldsymbol{r})/(2\pi r)$: energy per unit area
- ✓ $g(z)$: 1D Gaussian kernel
  - ➢ z_{rotor} : location of rotor disk plane
  - ➢ $\sigma = 0.2 c_{75}$: standard deviation

Methods: UTCart (rotational frame)

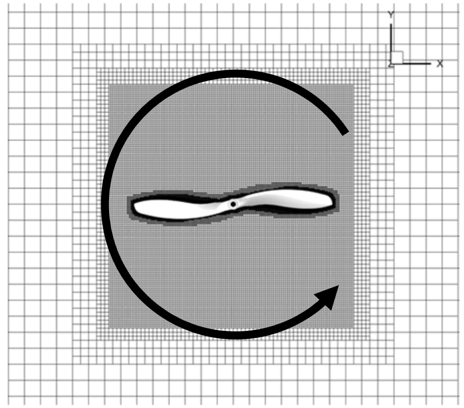
- Extended version of UTCart to rotational frame*
  - ✓Limited to single rotating grid (no overset)
    - ➢Only single rotor (Multiple rotor cannot be handled)
    - ➢No airframe (Wing, Fuselage, etc.)
  - ✓Modification to UTCart
    - ➢$\boldsymbol{W}$: velocity vector of the grid

$$\frac{\partial}{\partial t}\int_V \boldsymbol{Q}_c\, dV + \int_{\partial V}\{(\boldsymbol{F}(\boldsymbol{Q}_c) - \boldsymbol{Q}_c \otimes \boldsymbol{W}) - \boldsymbol{F}_v\}\cdot \boldsymbol{n} ds = 0$$

$$(\boldsymbol{F}(\boldsymbol{Q}_c) - \boldsymbol{Q}_c \otimes \boldsymbol{W}) \cdot \boldsymbol{n} = T^{-1}\boldsymbol{F}(T\boldsymbol{Q}_c)\cdot \boldsymbol{n}$$

where

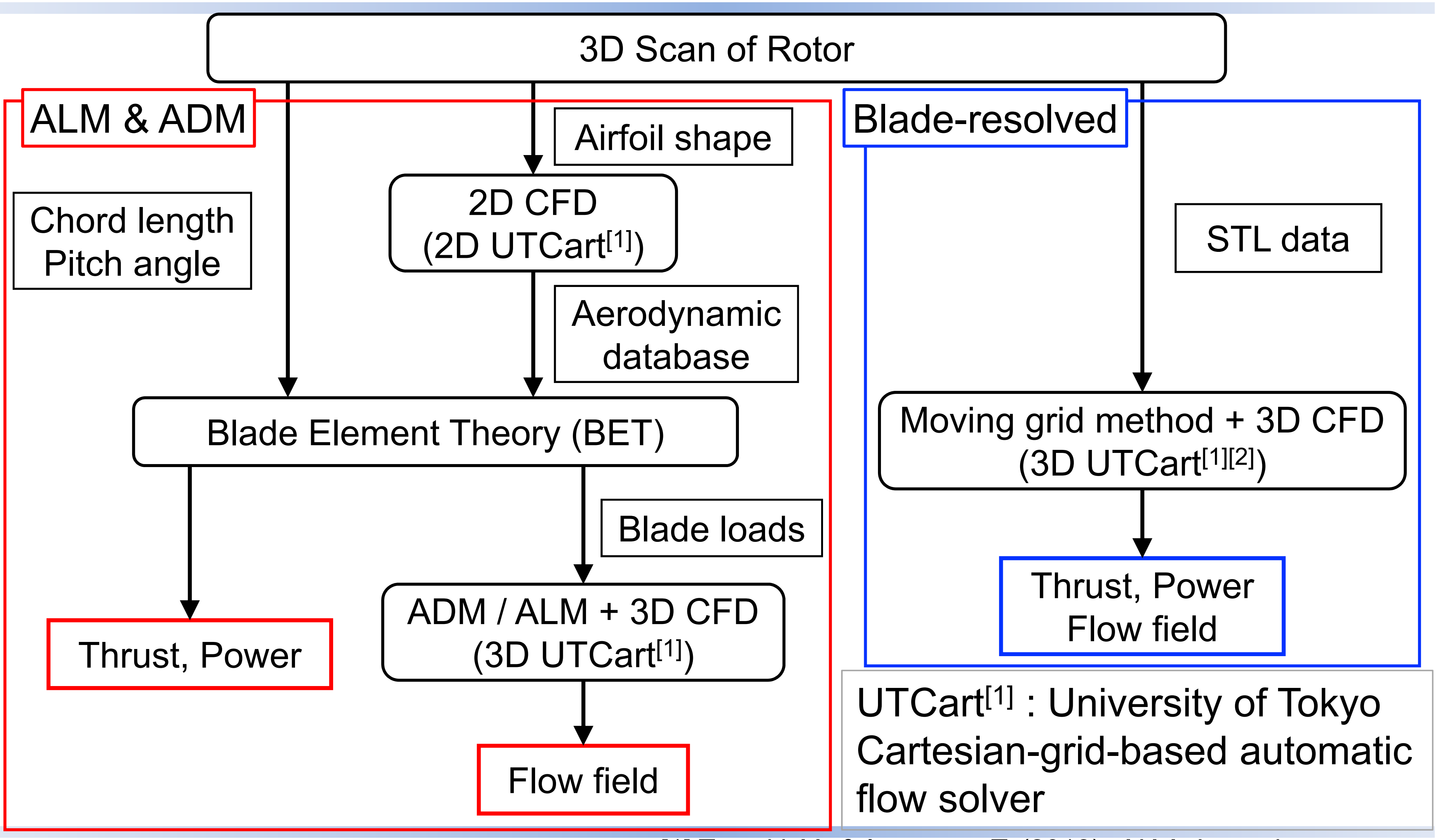
$$T = \begin{bmatrix} 1 & 0 & 0 \\ -\boldsymbol{W} & 1 & 0 \\ |\boldsymbol{W}|^2/2 & -\boldsymbol{W}^{\mathrm{T}} & 1 \end{bmatrix}$$



The grid rotates with the rotor

* Sugaya, K., and Imamura, T. Computers & Fluids 2021

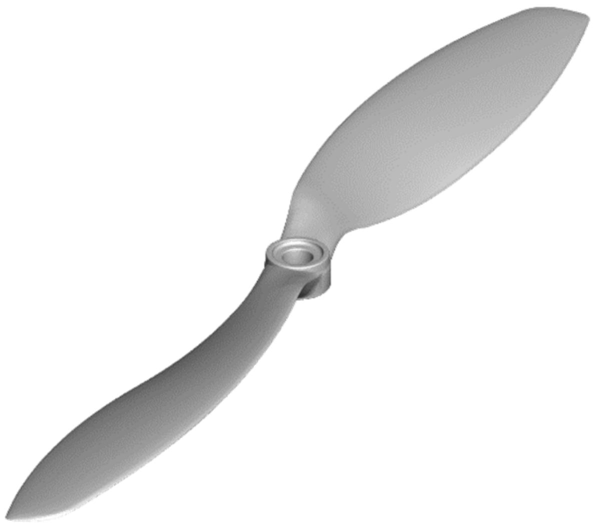
Methods: Flowchart of the analysis



UTCart[1] : University of Tokyo Cartesian-grid-based automatic flow solver

[1] Tamaki, Y., & Imamura, T. (2018). *AIAA Journal*.
[2] Sugaya, K., & Imamura, T. (2021). *Computers & Fluids*.

Single rotor simulation



Single rotor simulation

- ✓ Code verification
- ✓ Validation of wake flow field

Hexacoptor simulation

- ✓ Rotor-airframe interaction
- ✓ Evaluation of comp. cost

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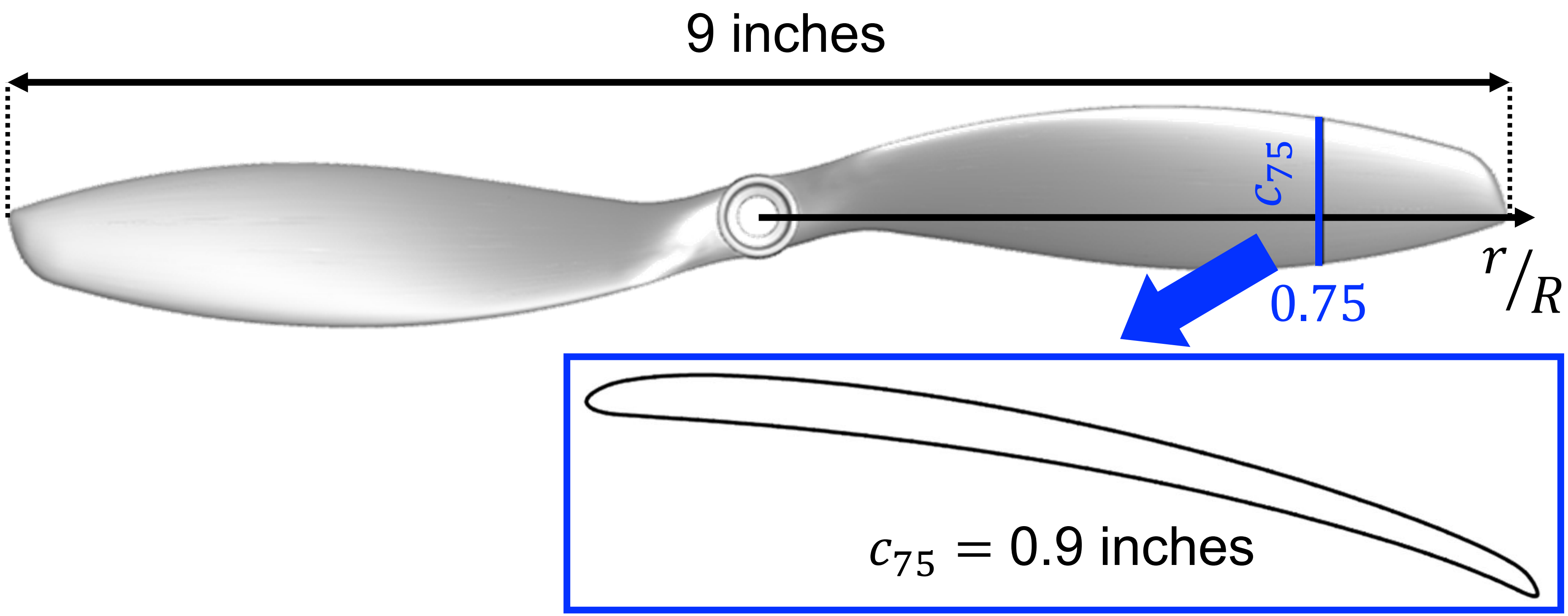
Simulation setup: Geometry

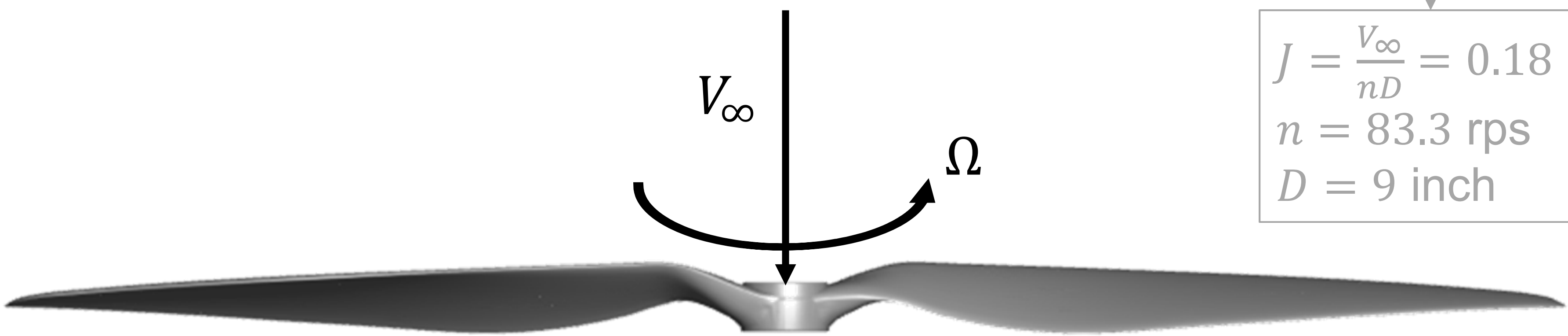
- A fixed-pitch rotor for a small UAV
  - ✓APC 9×4.7 Slow Flyer
    - ➢Diameter : 9 inches
    - ➢Pitch : 4.7 inches



Simulation setup: Flow conditions

- Rotation speed : 5,000 RPM ($\Omega = 523.6$ rad/s)
  - ✓Calculation of 15 total rotations
- $Re_{75} = 7.03 \times 10^4$
  - ✓Reynolds number based on the chord length c_{75} and blade rotational speed Ωr_{75} at $r/R = 0.75$
- Axial climb condition
  - ✓Axial inflow velocity $V_\infty = 3.4$ m/s

$J = \frac{V_\infty}{nD} = 0.18$
$n = 83.3$ rps
$D = 9$ inch



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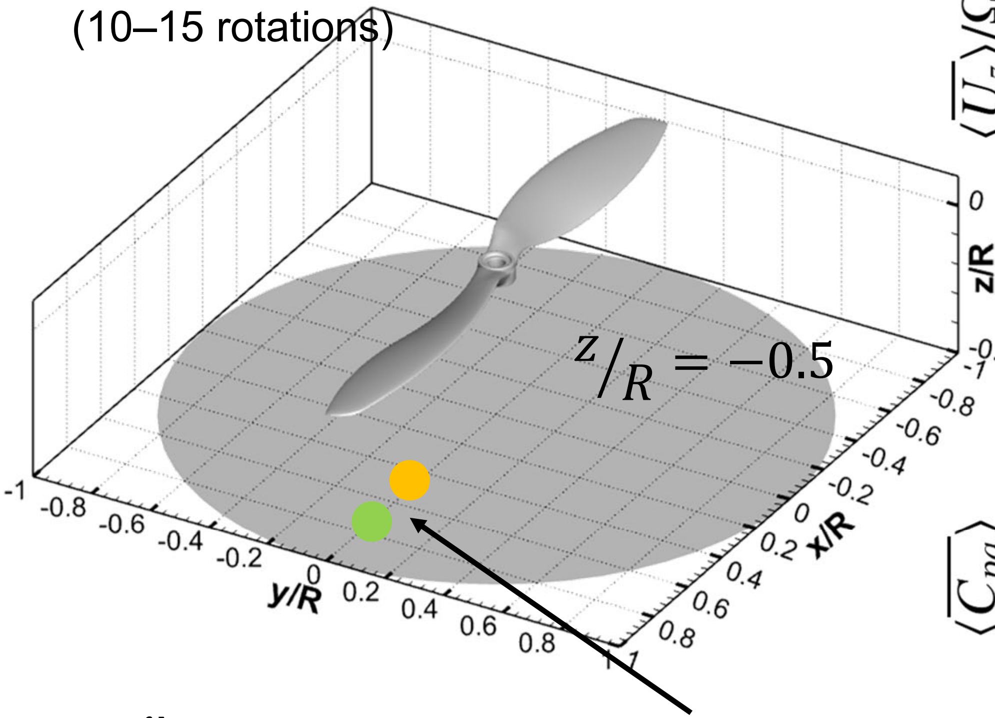
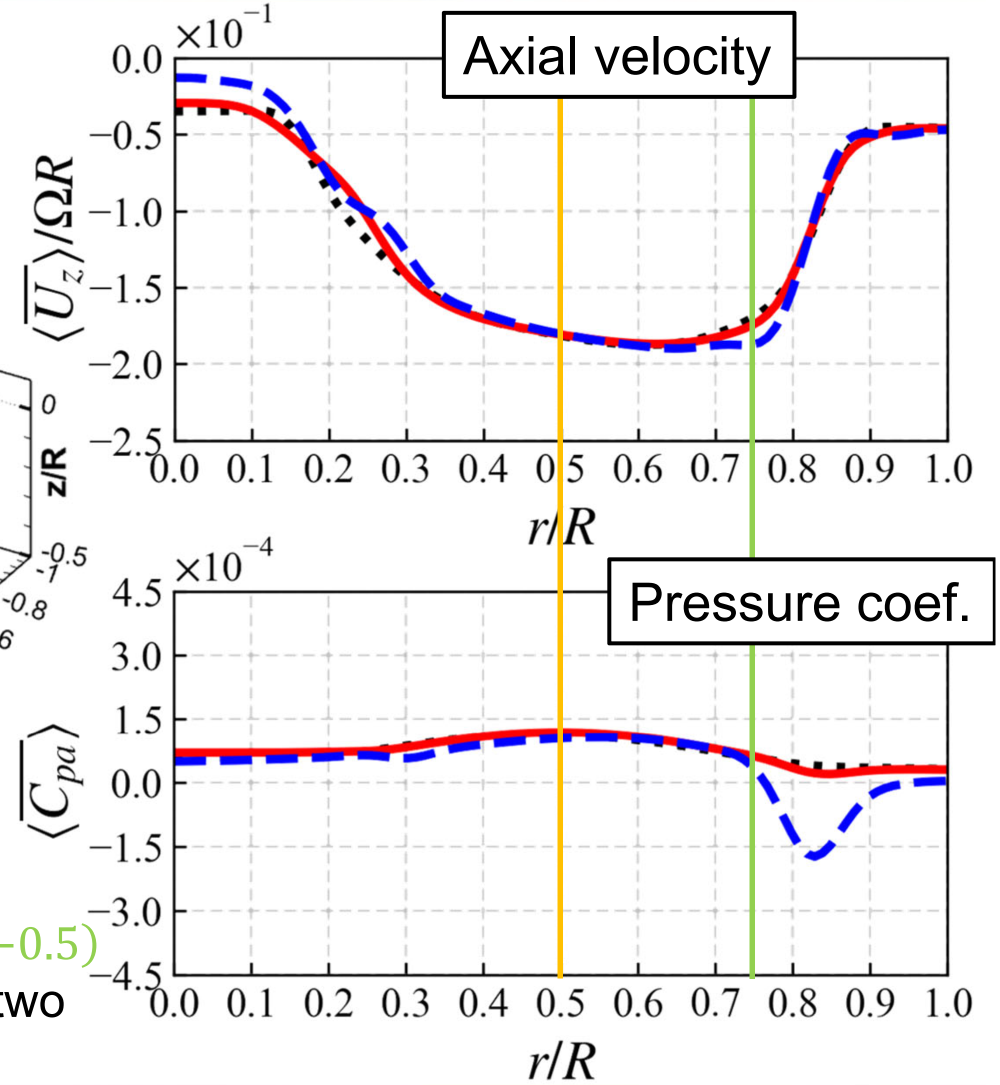
Result: Time-averaged wake

ALM ······ ADM – – Direct

Time-averaged over the final 5 rotations (10–15 rotations)

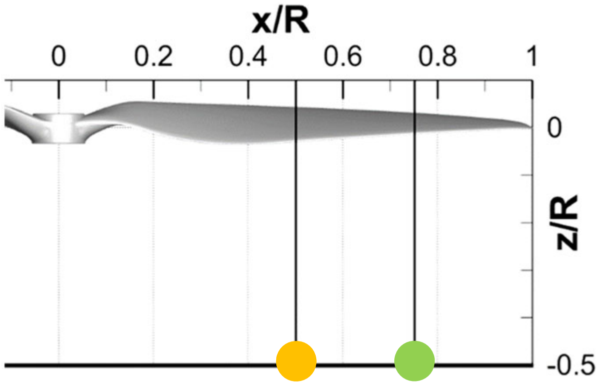




$(x/R, y/R, z/R) = (0.5, 0.0, -0.5), (0.75, 0.0, -0.5)$

Time variation of velocity and pressure at two observation points

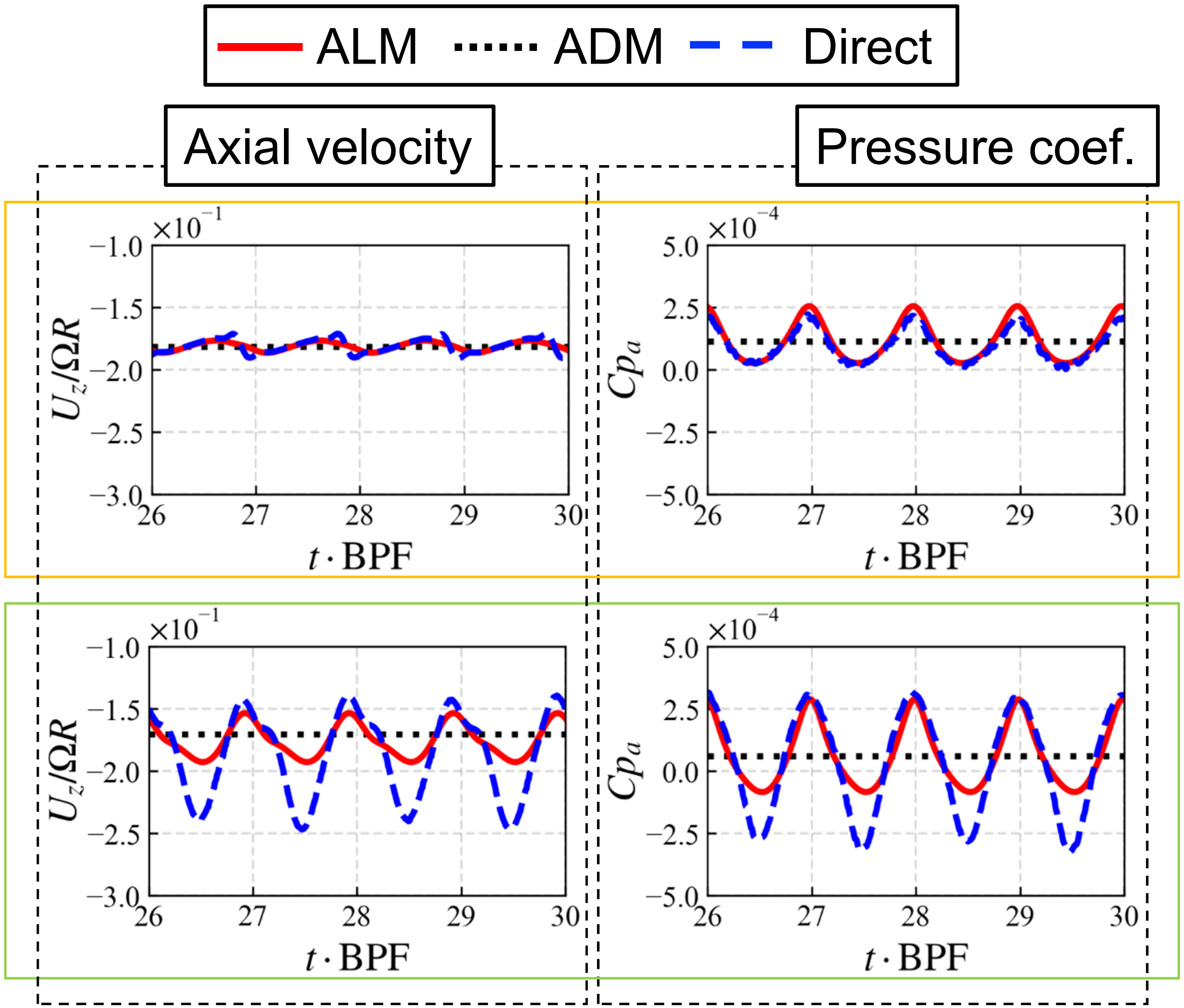
Result: Time-variation of the wake



Prediction accuracy of ALM

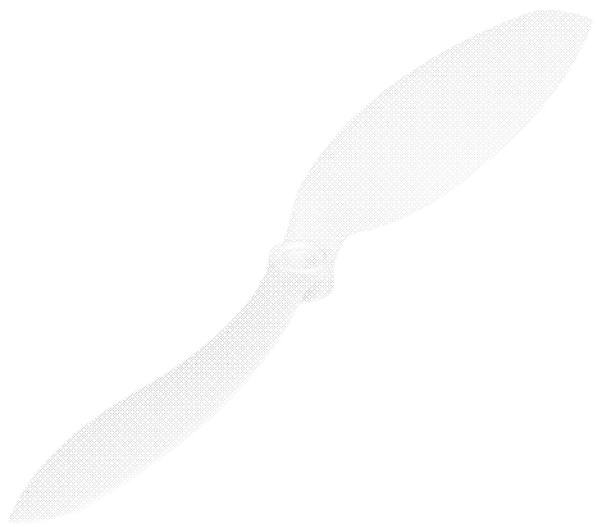
Root side ($x/R = 0.5$)
- Good agreement

Tip side ($x/R = 0.75$)
- Amplitude is underestimated
- Phase, period good



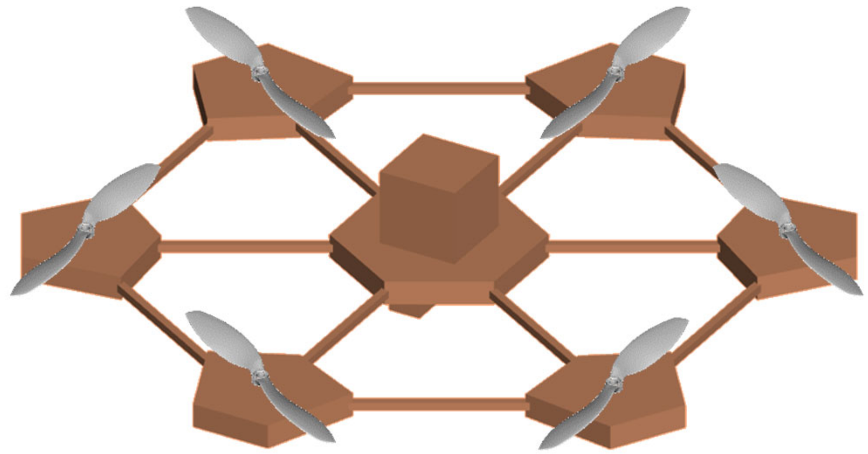
$\mathrm{BPF} = N_b \cdot \mathrm{RPM}/60$
Blade Passing Frequency

Hexacoptor simulation



Single rotor simulation

- ✓ Code verification
- ✓ Validation of wake flow field



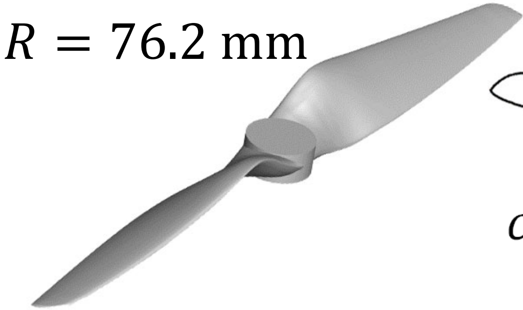
Hexacoptor simulation

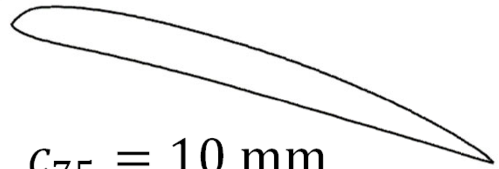
- ✓ Rotor-airframe interaction
- ✓ Evaluation of comp. cost

Simulation setup: Geometry etc.

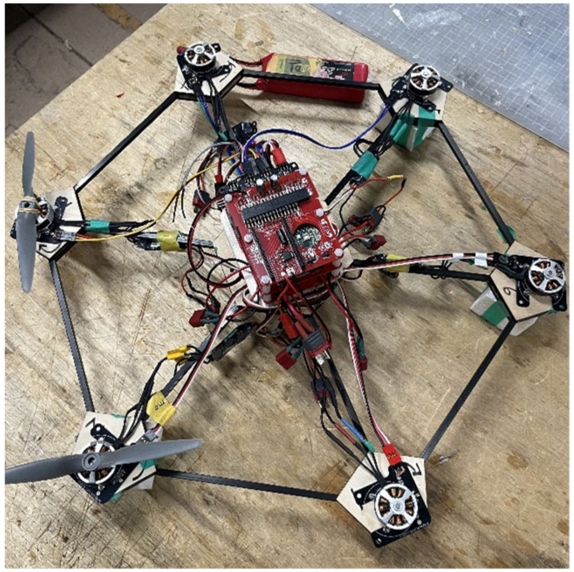
- Geometry
  - ✓Blade: APC 6×4E
  - ✓Hexacoptor [1]
- Condition
  - ✓9,000 RPM、$Re_{75} = 3.41 \times 10^4$
  - ✓Hovering

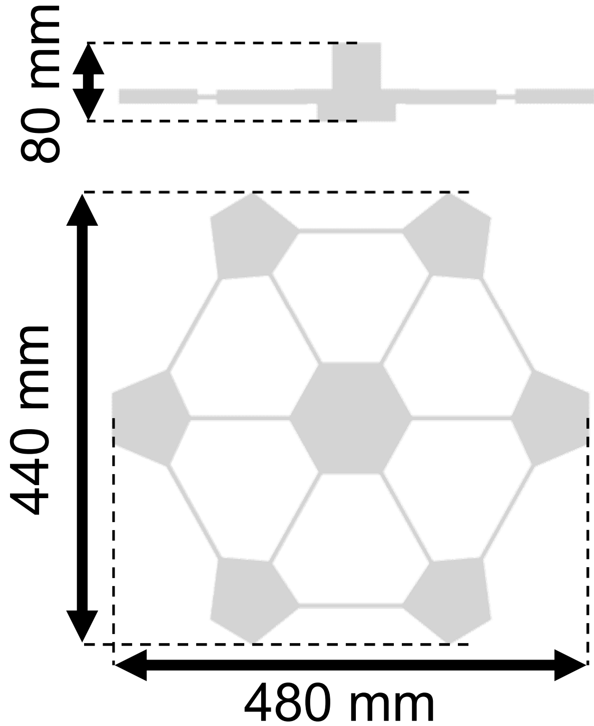
$R = 76.2\ \mathrm{mm}$





$c_{75} = 10\ \mathrm{mm}$

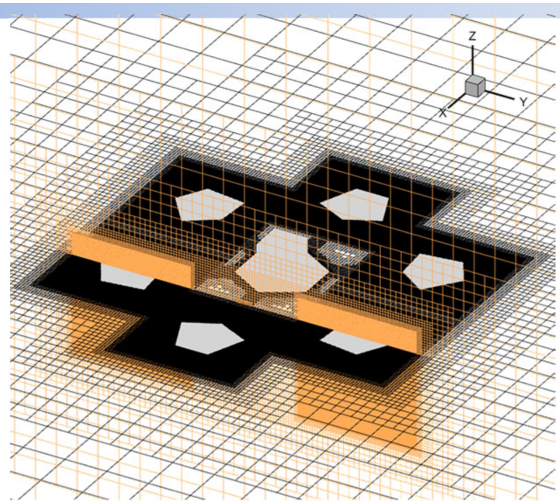


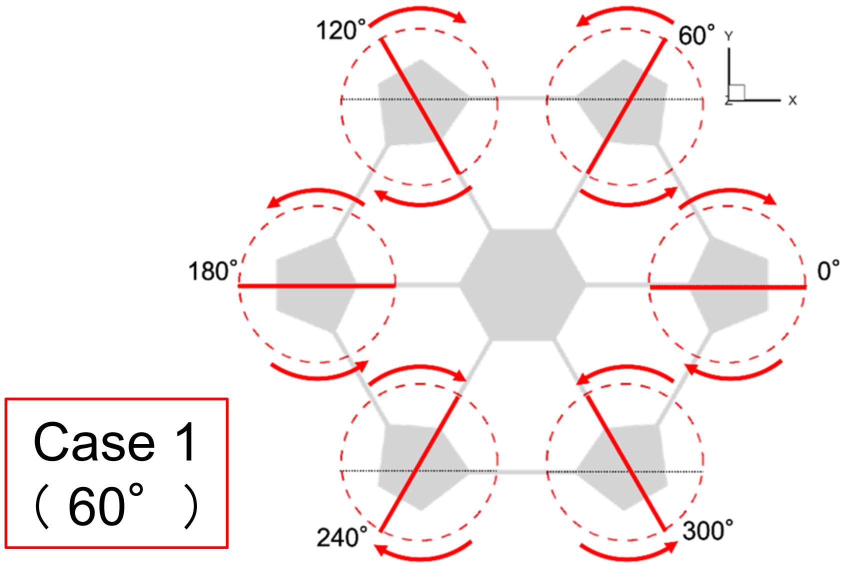


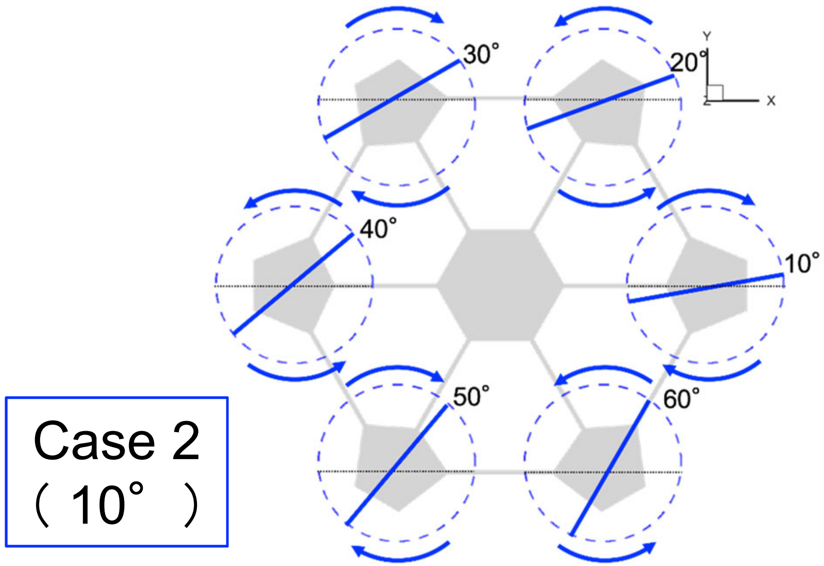
[1] Developed by Assistant Prof. Naoto Morita at The University of Tokyo

Simulation setup: Grid etc.

- ALM
- Computational grid
  - ✓ # of grid points : 37,682,200
  - ✓ Min. grid size: $\Delta x_{\min} = 0.1 c_{75} = 1\ \mathrm{mm}$
- Number of rotation: 30



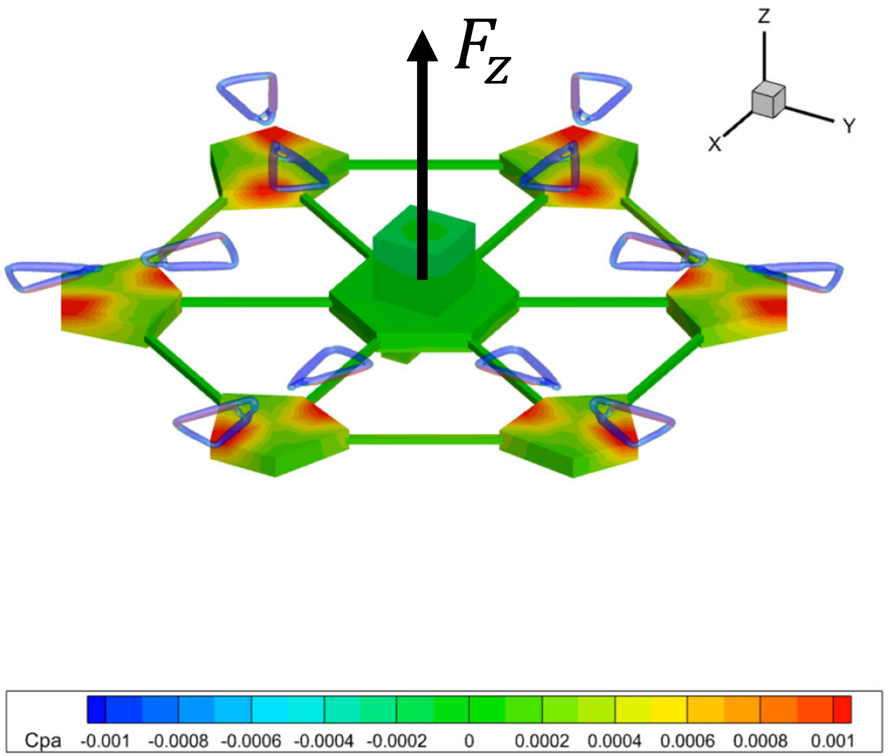




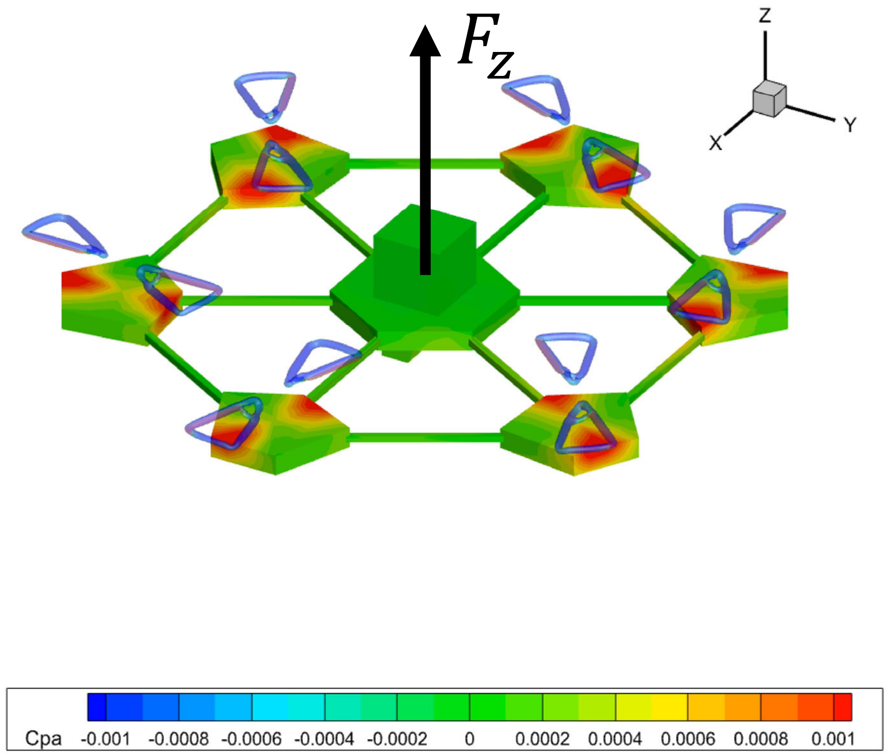
Results: Flow field

Isosurface of Q−value + Aircraft surface (colored by C_{p_a})

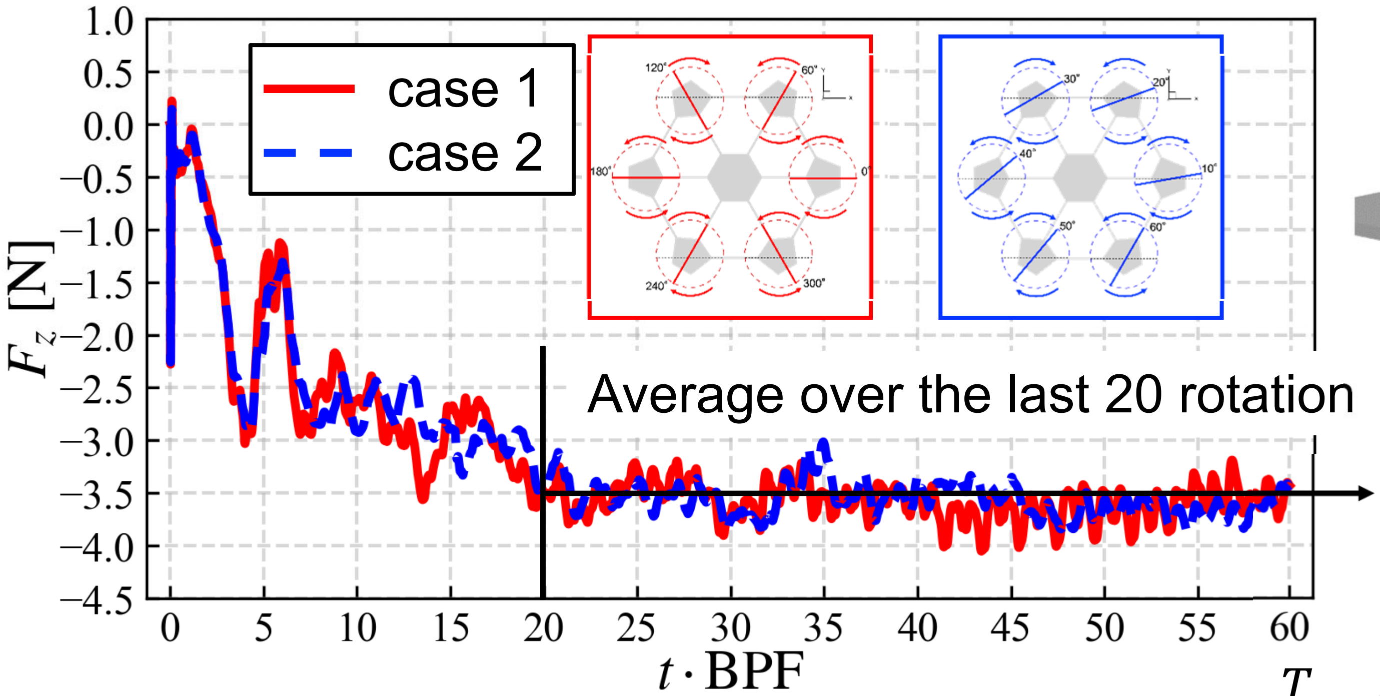
case 1

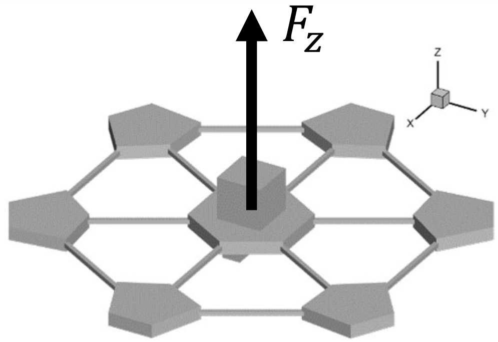


case 2



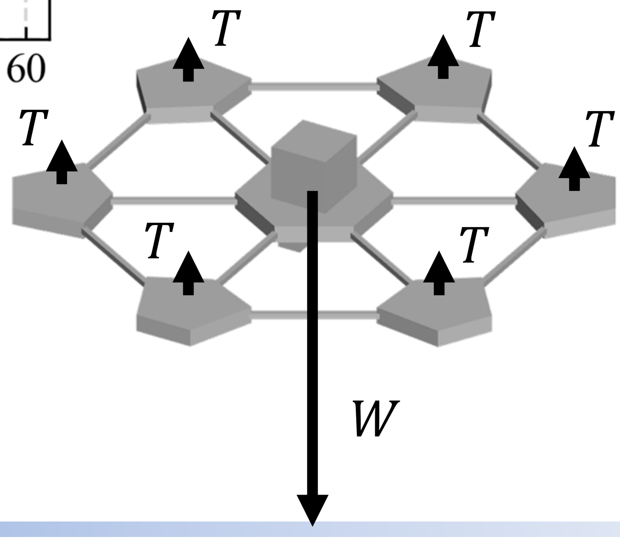
Results: Aerodynamic force on airframe(1)





$\overline{F_z} = -3.58$ N

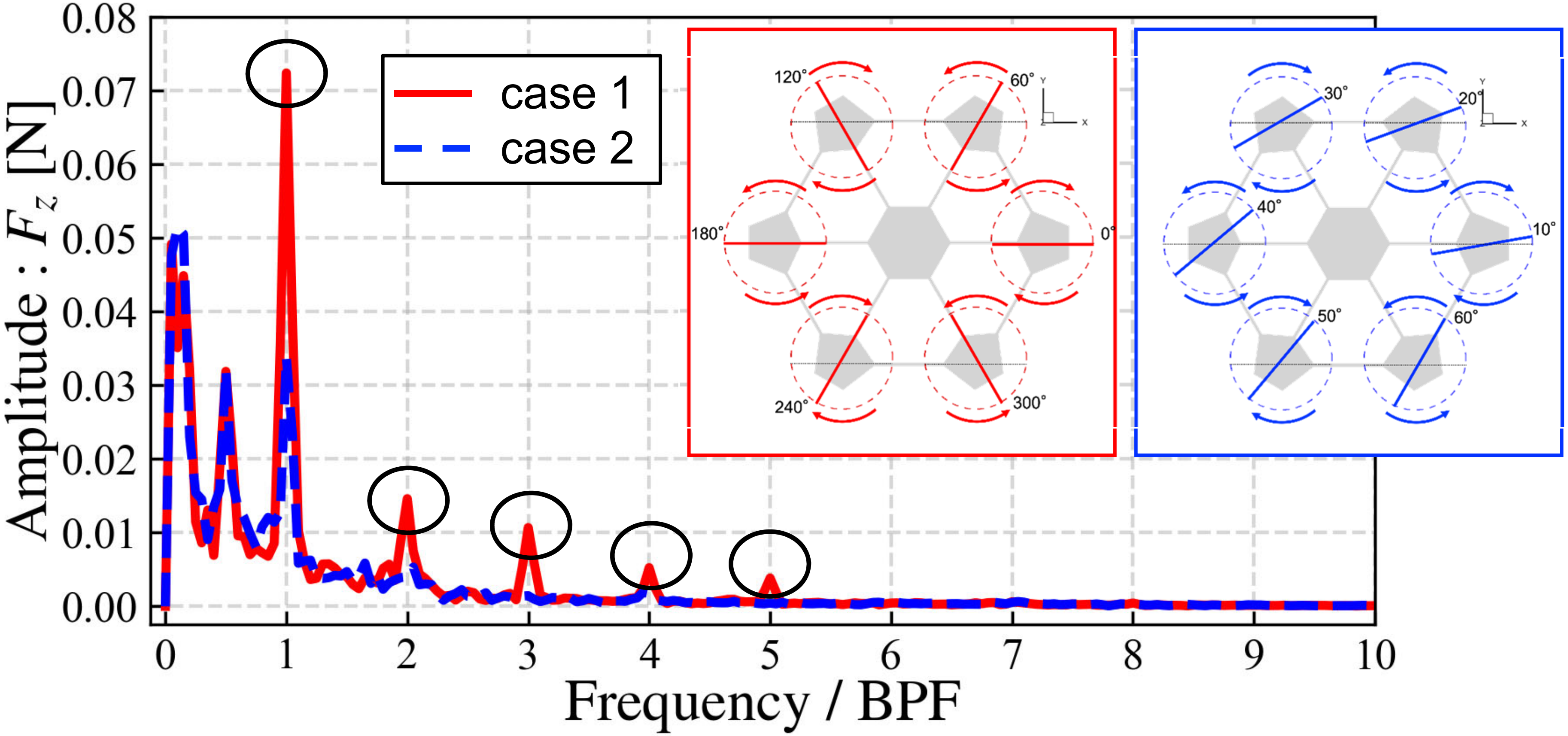
$\overline{F_z} = -3.56$ N



$\overline{F_z} = -3.57$ N

✓ Thrust from single rotor（$T_{\mathrm{BET}} = 1.55$ N）

Results: Aerodynamic force on airframe(2)



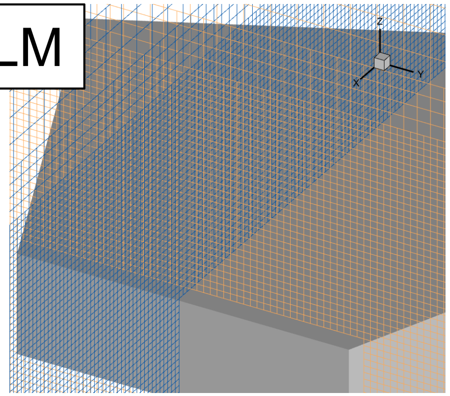
The aerodynamic interaction experienced by the airframe depends on the phase of the rotor

Results: Computational Cost

- 計算時間※
  - ✓768 parallel, 39 hours
    - ➢1.3 hours per rotation

※ Wisteria/BDEC-01 (UTokyo super computer)

ALM



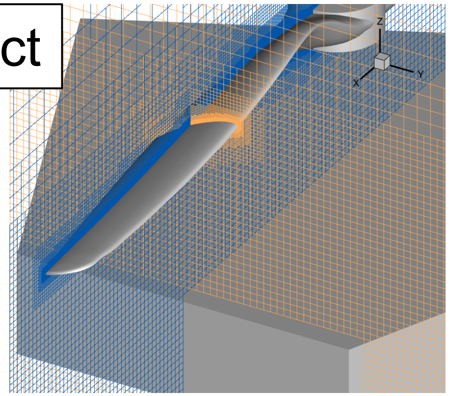
- 直接計算との比較

(Estimated)

Approach	# of grid	steps / rot.	Cost
ALM	38M	3,600	1.35×10^{11}
Direct	680M	230,400	1.56×10^{14}

1/1000

Direct



壁面（ローター）付近の細かい格子は ALM では不要
✓ 格子の数を削減
✓ 大きな時間ステップ→1回転あたりの計算ステップ数を削減

まとめ

- ロータ後流の非定常な流れを低コストで再現できる三次元流体解析手法の構築とその性能評価
  - ✓Blade Element Theory とActuator Line Model の組み合わせ
- Single rotor analysis
  - ✓定常・非定常流れ場の再現が可能であることを実証
- Hexacopter analysis
  - ✓ローターによって機体が受ける空力相互作用を評価
  - ✓直接計算と比較して、ALMの計算コストは1/1000程度