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Advanced Compound Helicopter Research and Development

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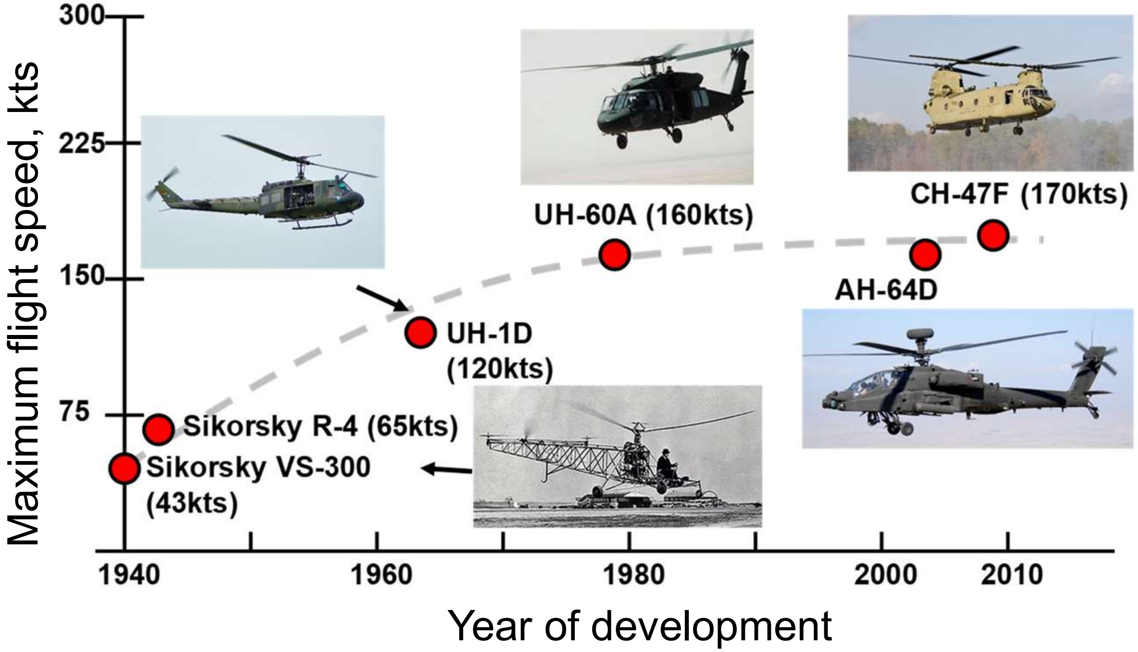
Japan Aerospace Exploration Agency (JAXA)

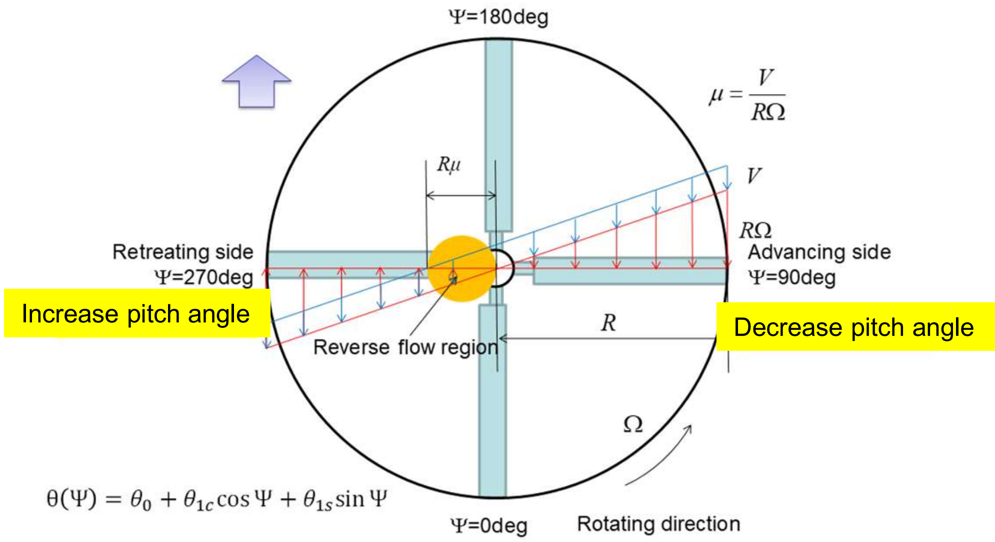
Outline

- Background and objectives
  - History and recent developments of compound helicopters
  - A conceptual study of high-speed compound helicopter at JAXA
- Technology Issues related to high-speed compound helicopters
  - Optimal rotor design for high advance ratio flight
  - Rotor/Wing Interaction and Single-rotor Lift-offset
  - Rotor/Propeller Interaction
  - Low drag fuselage
- Realization of a high-efficiency compound helicopter through applying the advanced technologies
- Spin-off effects
- Summary and future works

Background: the conventional helicopter performance limitation



Conventional helicopter maximum flight speed history



Inflow to the rotor blade and control of the rotor blade pitch angle

History of Compound Helicopters

Fig. 2-5. The Fairey Rotodyne was successfully developed, but British Government and civil funding eroded in the late 1950s. This was the largest compound helicopter ever flown. Its maximum advance ratio was below 1.

Fig. 2-4. The McDonnell Aircraft Corp., Helicopter Division's XV–1 Convertiplane. At maximum speed, the rotor operated at an advance ratio just below 1.

Lockheed AH-56 Cheyenne
Development: 1966-1972, 215kt, mu~0.52

Fig. 2-9. The DARPA funded Groen Brothers Heliplane is expected to reach 400 mph with the rotor operating at an advance ratio near 2.

Ref) Harris

Recent Developments of High-Speed Rotorcraft

Bell-Boeing V-22 Osprey
Development：1982-1997：
In production: 1997~,
max 275 kt, cruise 241 kt

Sikorsky X-2
Development: 2008-2010, max 250 kt, mu~0.65

Airbus Helicopters X3
Development: 2010-2013, max 255 kt, mu~0.7

On-going Developments of Compound Helicopters

Sikorsky S-97 Raider
Vne 240 kt, Cruise 220 kt
In test flight

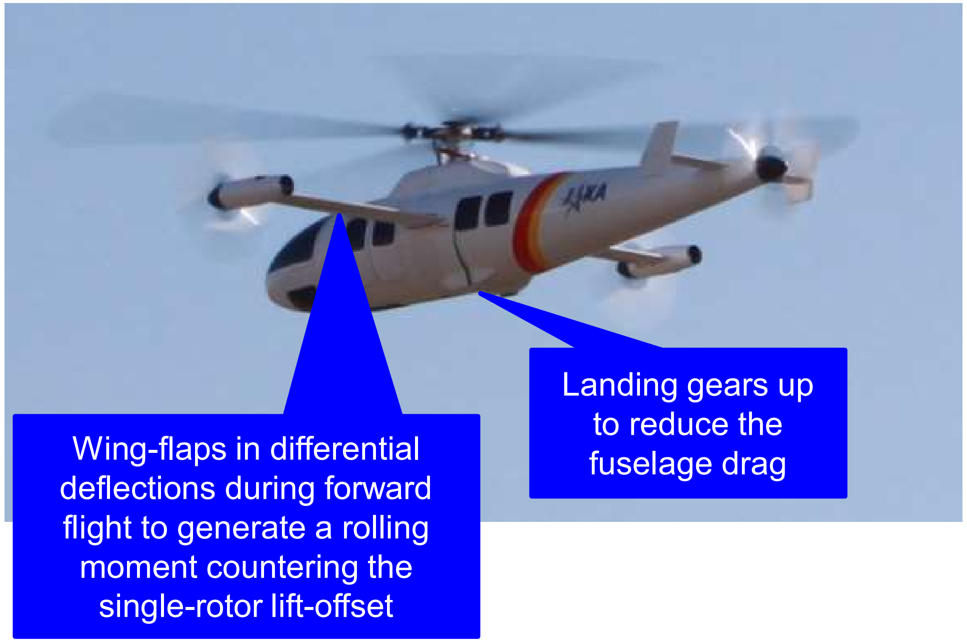
Airbus Racer
Cruise 217 kt ?
First flight expected in 2022

A Concept of Compound Helicopter Proposed by JAXA

・Designed for EMS of 4 ton class
・Electric driven anti-torque propellers at wing-tips
・Aft-mounted pusher propeller
・Target max speed: 500km/hr (270 kts)
・Max advance ratio, mu=0.8

Ref) Tanabe Y, Aoyama T, Kobiki N, Sugiura M, Miyashita R, Sunada S, Kawachi K, and Nagao M, ***A conceptual study of high speed rotorcraft***, 40th European Rotorcraft Forum, Southampton, UK, Sept. 02-05, 2014.

Additional Design Features



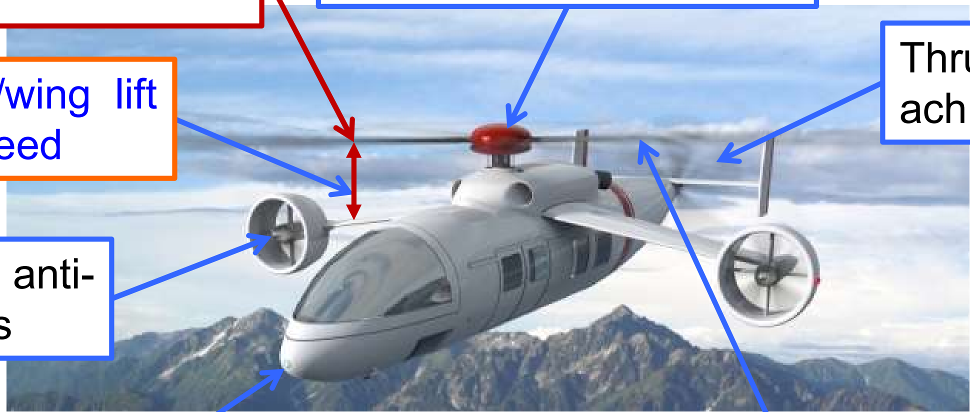
Technology issues for high-speed compound helicopter

Rotor/Wing aerodynamic interaction

Low aerodynamic drag rotor hub

Optimized rotor/wing lift share at high speed

Thrust propeller to achieve high speed



Electrical driven anti-torque propellers

Low aerodynamic drag fuselage

Advanced rotor blades optimized for high advance ratio flight

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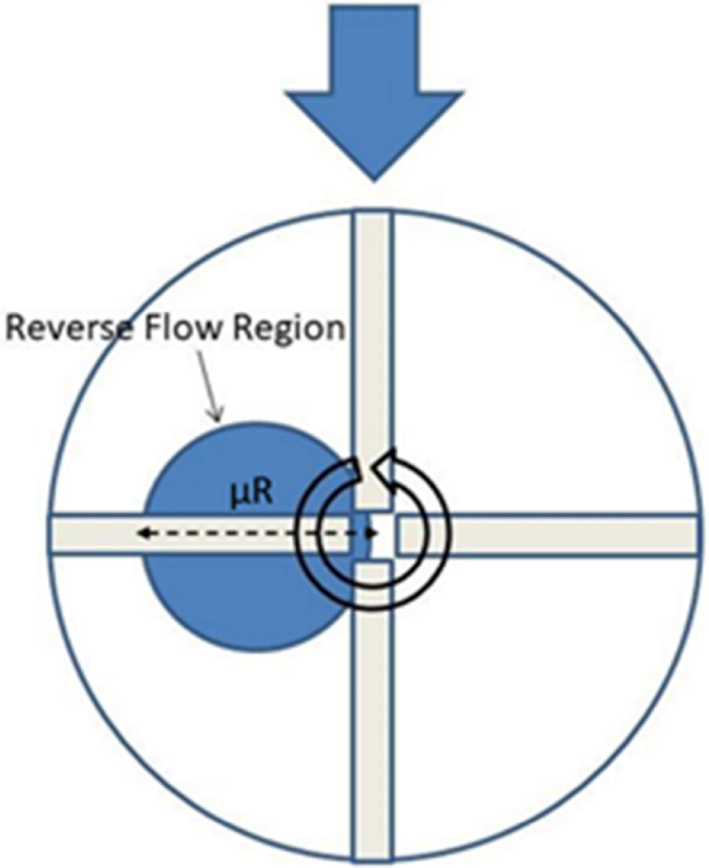
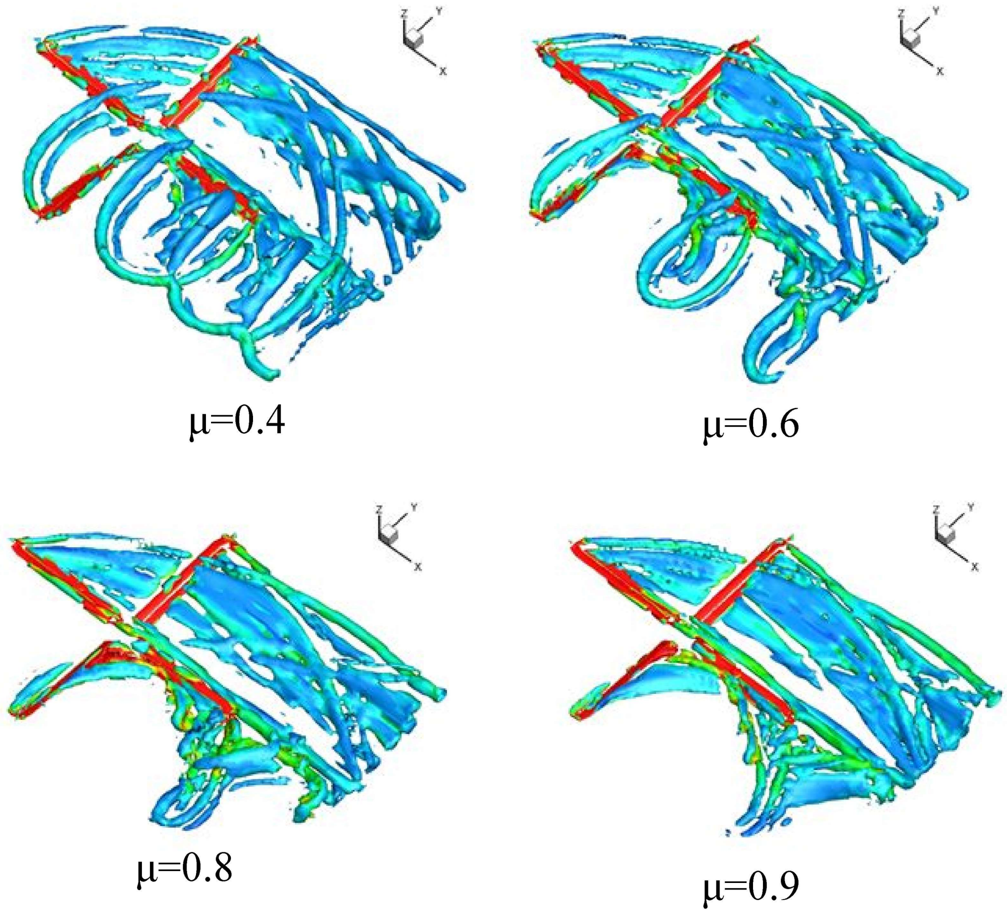
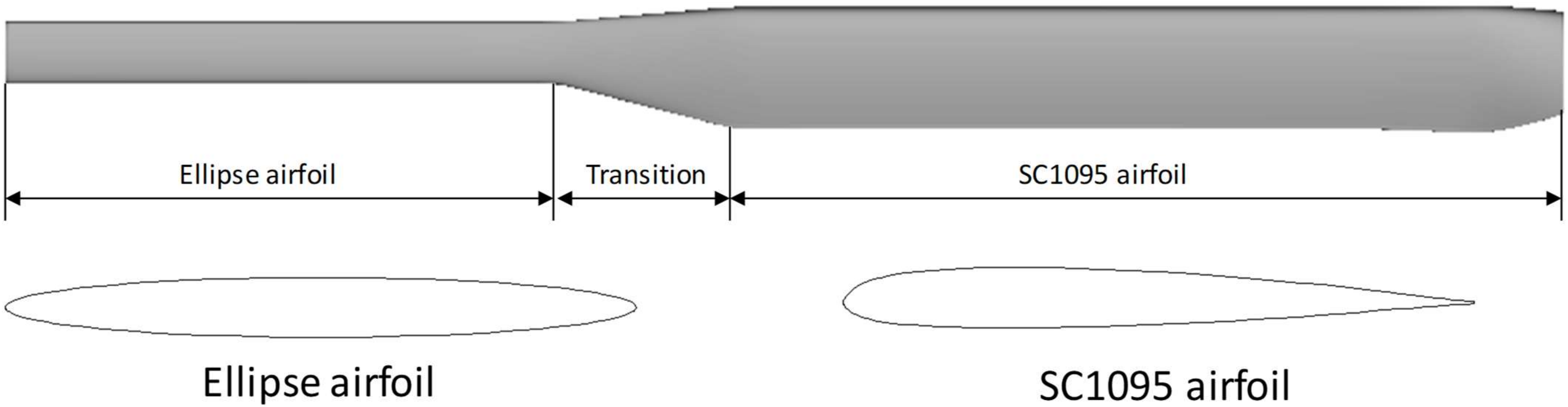
Optimal Rotor Design for High Advance Ratio Flight



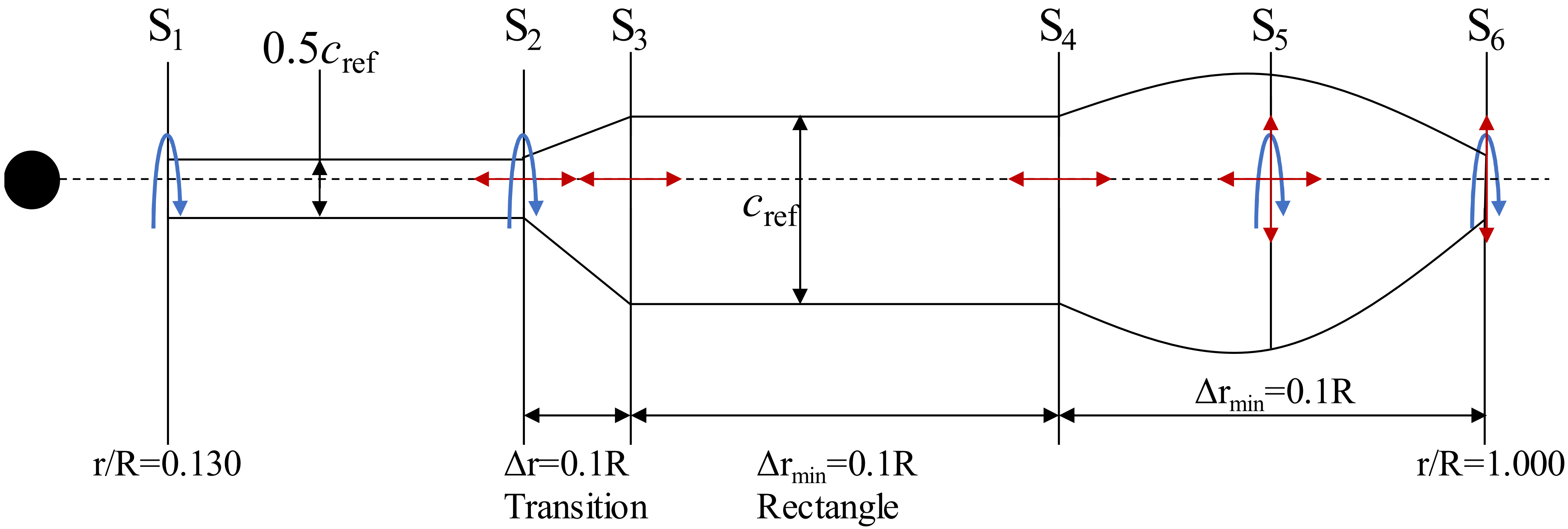
Reversed flow region at high advance ratio



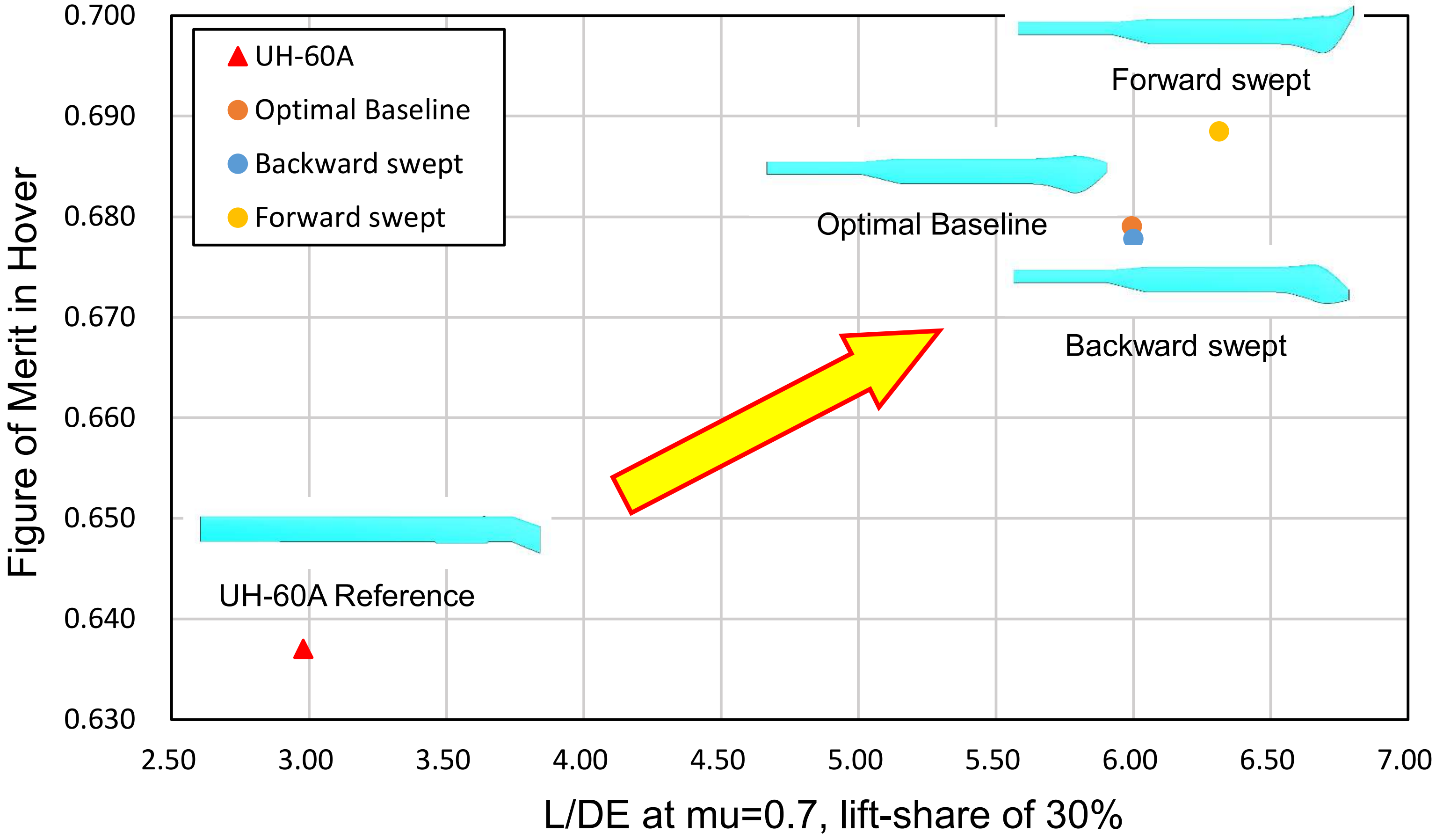
Large root-cut blade design for high-mu flight



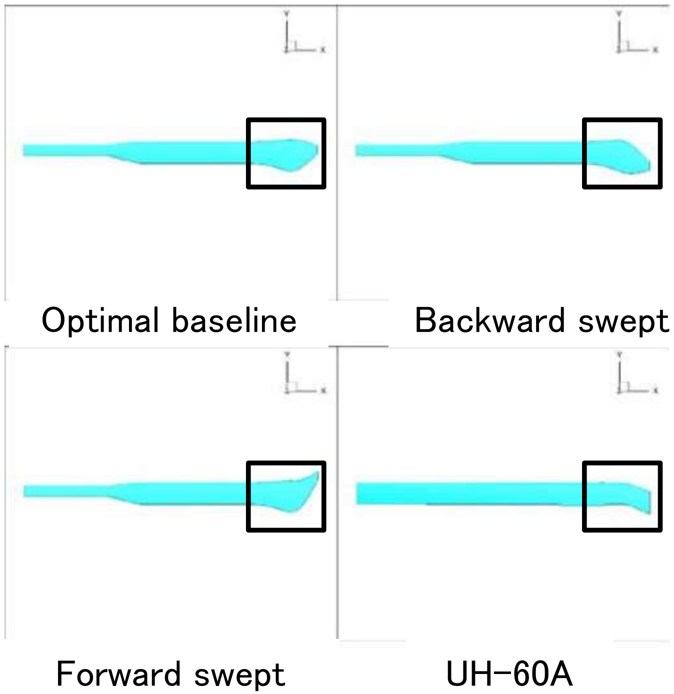
Design variables for chord and twist



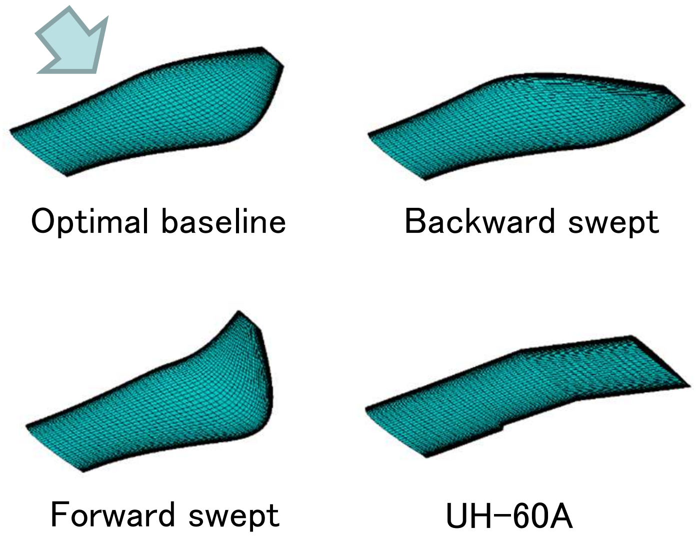
Optimal rotor for flight at mu=0.7, effect of swept angle



Wind-tunnel testing of the tip portions



Portion of blade tips (20%) are picked up



Blade-tip models

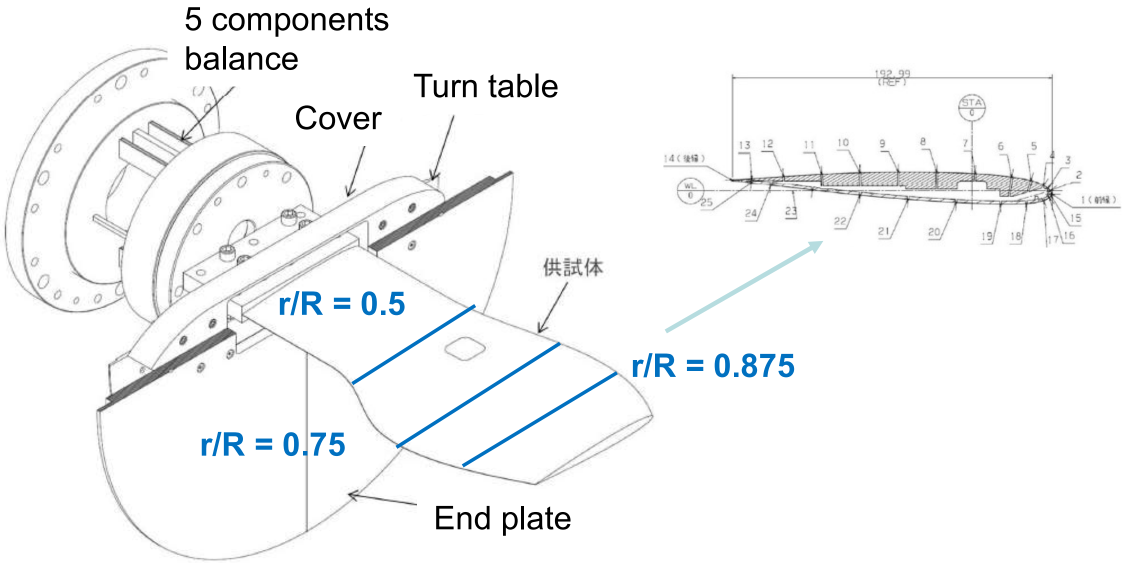
Optimal Baseline

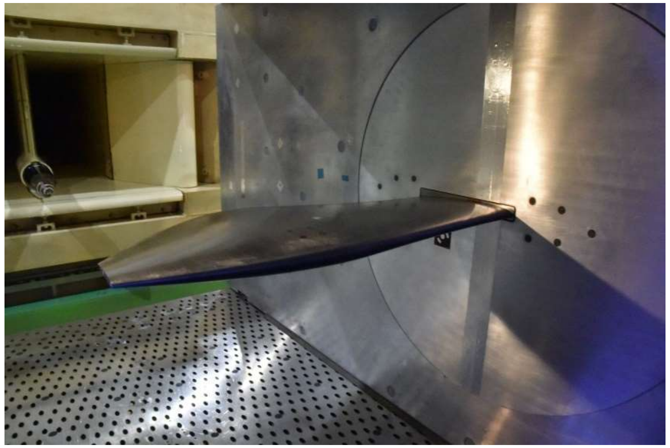
Backward swept

Forward swept

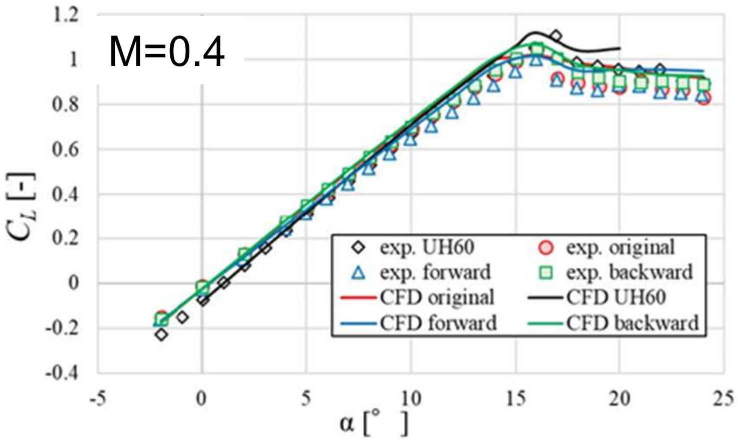
UH-60A

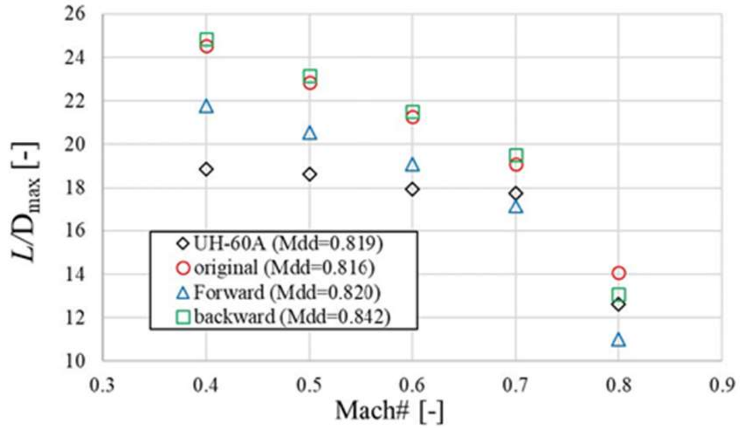
About 1/2 scale

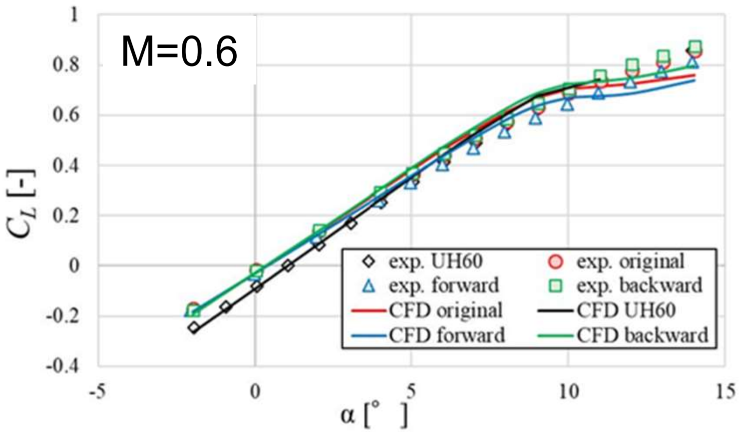




Aerodynamics of blade tips

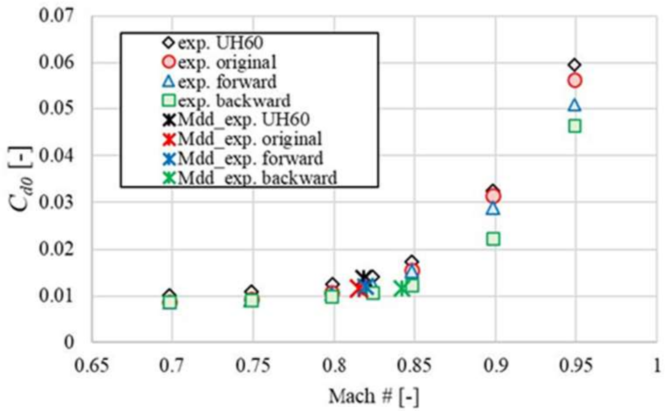






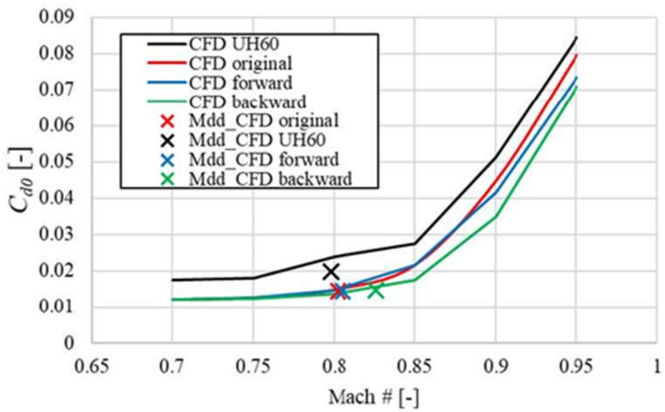
Ranking of L/Dmax at M=0.6：
1) Backward
2) Baseline
3) Forward
4) UH-60A

Drag divergence Mach number of blade tips



	Mdd (exp.)	Mdd (CFD)	Swept Back Angle
Baseline	0.82	0.80	0.0˚
Backward	0.84	0.83	-30.5 ˚
Forward	0.82	0.81	25.3˚
UH-60A	0.82	0.80	20.0˚

Mdd：dCd/dM>0.1



Ranking of Mdd：
1) Backward
2) Forward
3) Baseline
4) UH-60A

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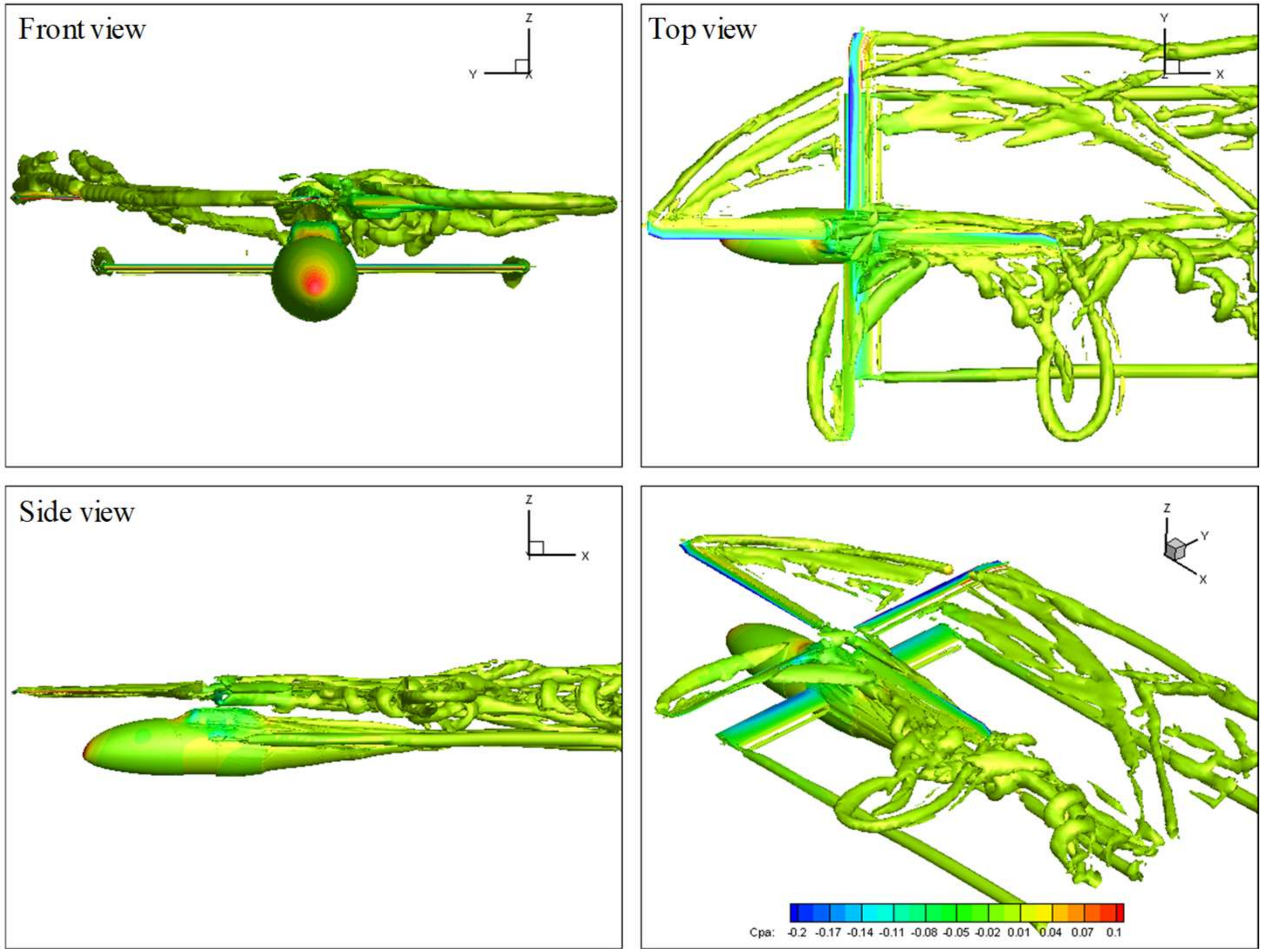
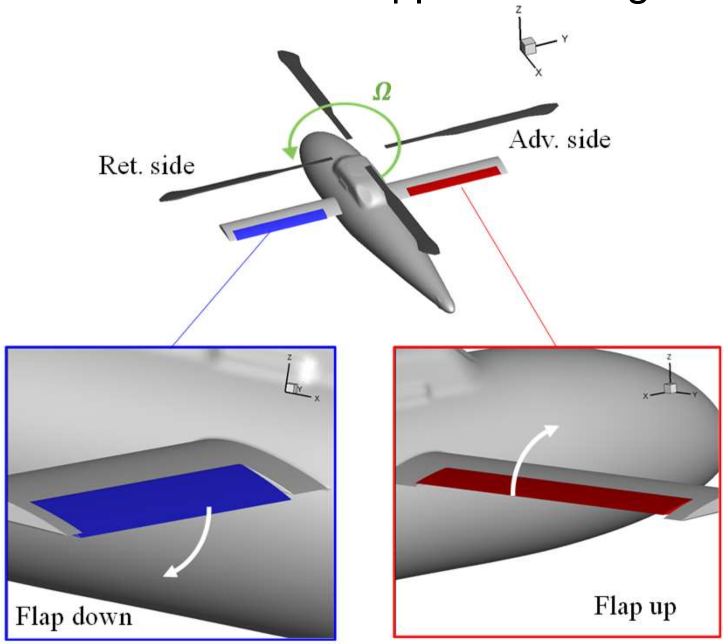
Rotor/Wing Interaction

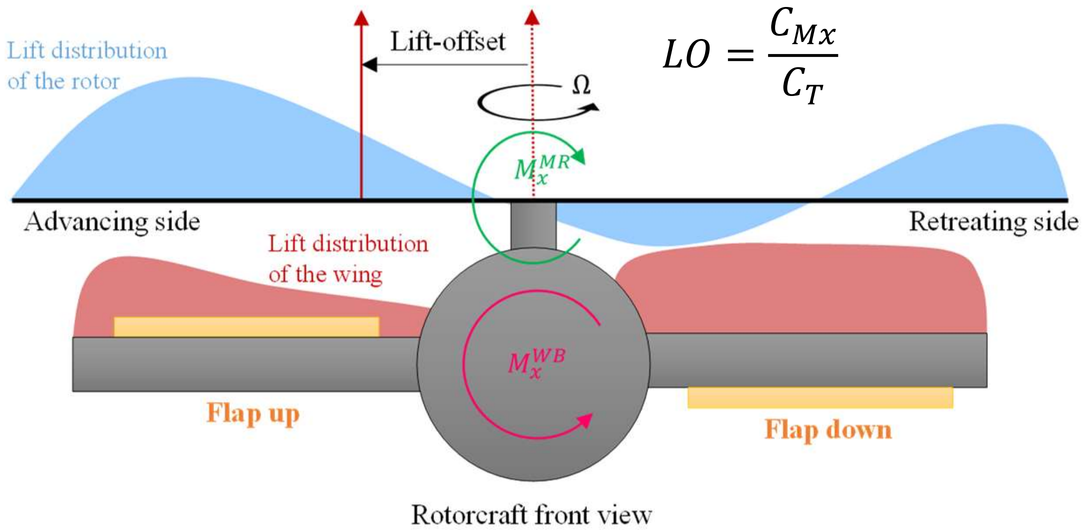


Single-Rotor Lift-Offset System

- Proposed differential flap system
  - Deflect upward under the advancing side, and deflect downward under the retreating side
    - Generate an imbalance of lift on the left and right wings resulting in a rolling moment
  - Expected to obtain a large rolling moment by small flap deflections
    - Occur rolling moment due to aerodynamic interaction

- The main rotor creates the opposite rolling moment and results in a single-rotor lift-offset state.

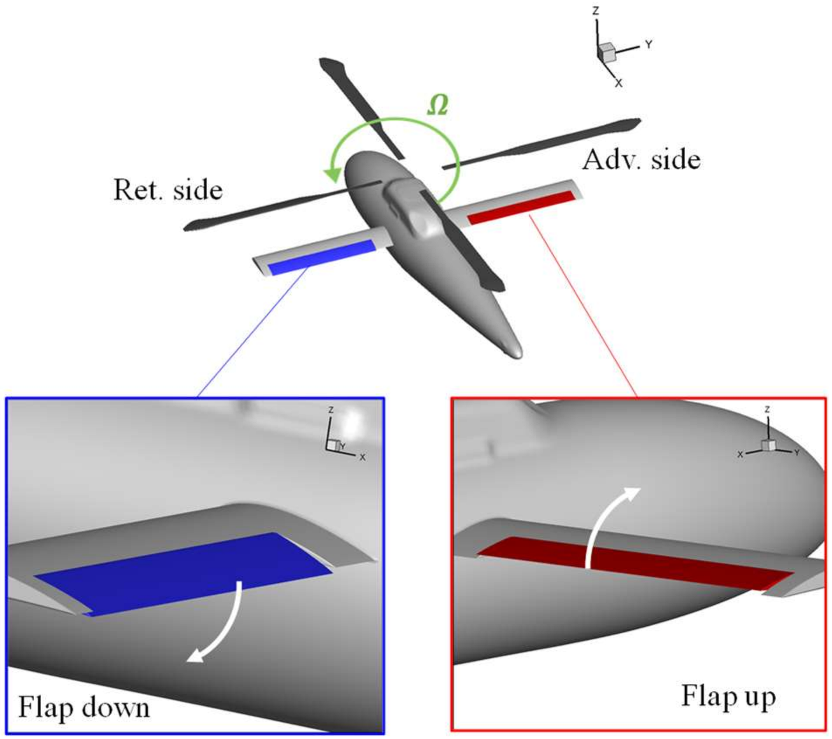


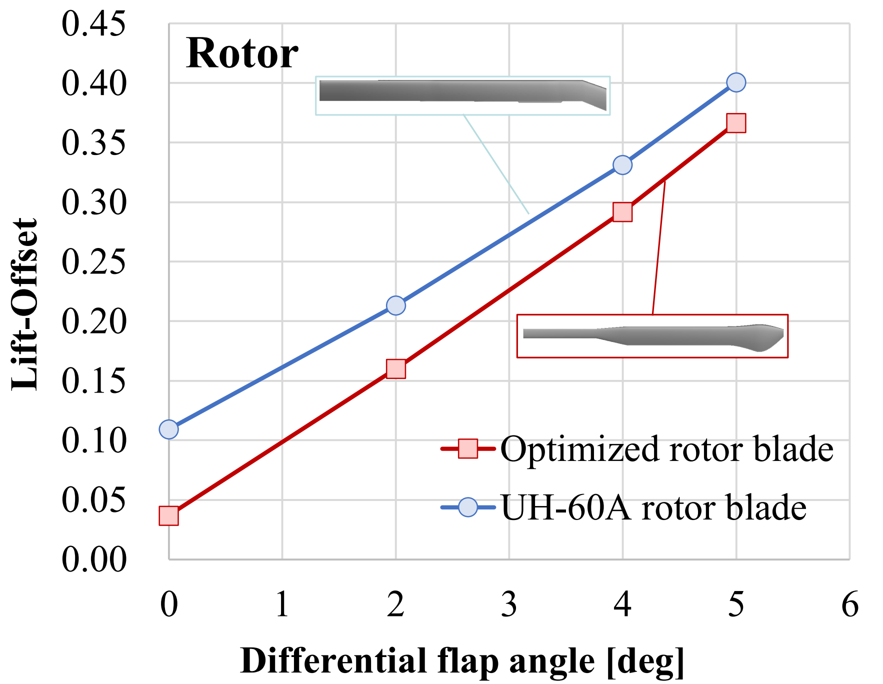


$$LO = \frac{C_{Mx}}{C_T}$$

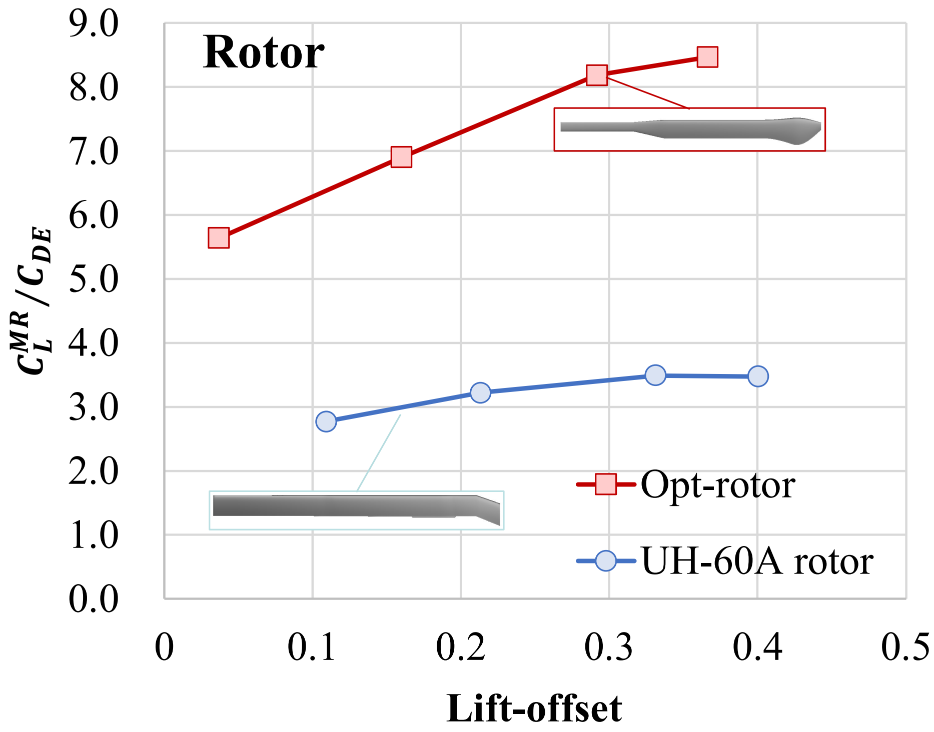
Lift-Offset by the Differential Flaps

- Obtain the maximum lift-offset values at the differential flap angle of 5 deg
- Arise the lift-offset due to the aerodynamic interaction even with zero flap deflection
  - Cause the effect of aerodynamic interaction on the wing with different type of rotors



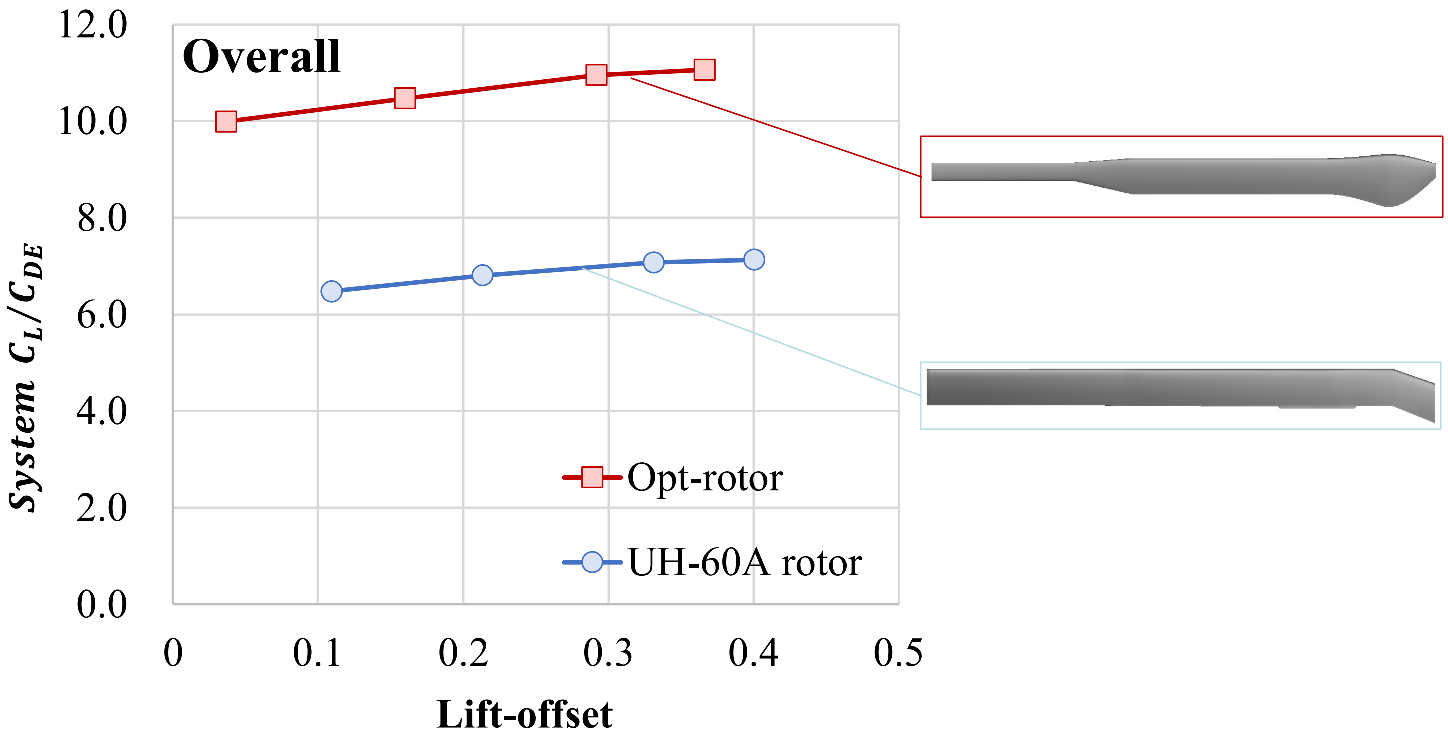


Effect of Lift-Offset on Rotor Performance



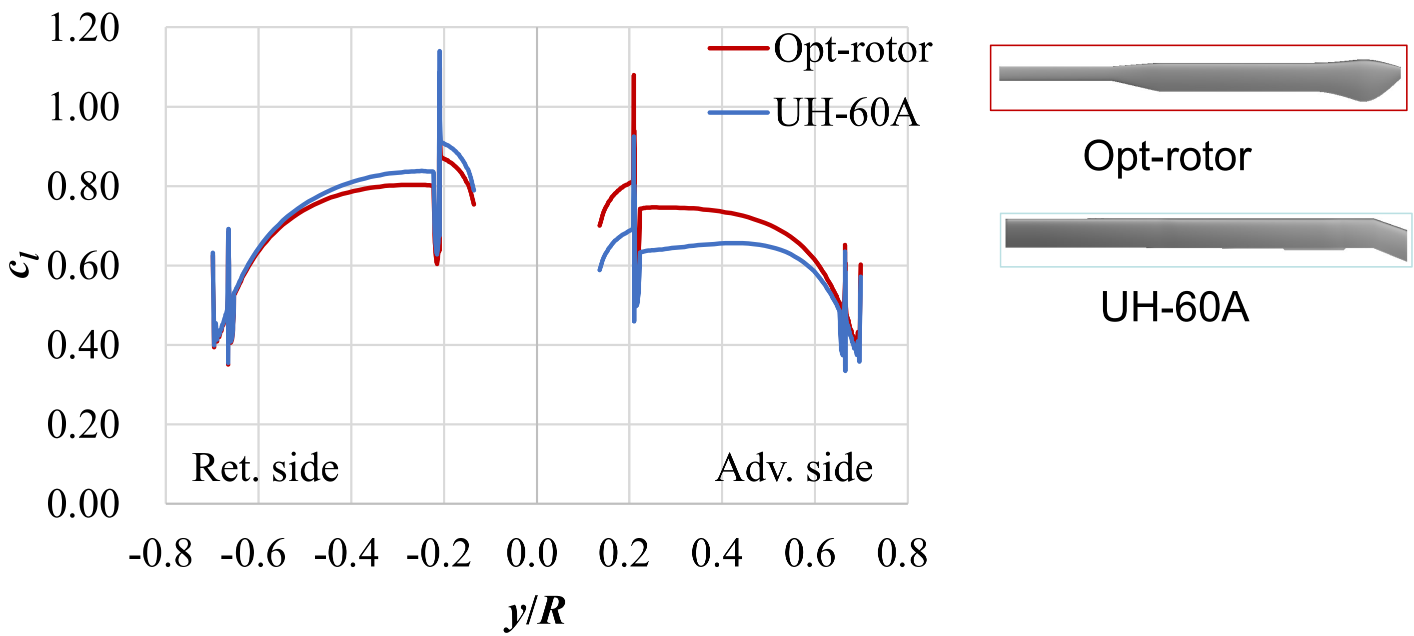
- Opt-rotor
  - Provide higher aerodynamic performance, approximately two times of the UH-60A rotor
  - Enhance by approximately 50% at the lift-offset of 0.37 compared with zero flap deflections
- UH-60A
  - Improves 25% at the lift-offset of 0.40 compared with zero flap deflections

Overall Performance



- The lift-to-drag ratio increases by 10% compared with zero flap deflections
- The opt-rotor is higher than the UH-60A rotor.
- The combination of improved rotor performance through optimization and lift-offset technology by the differential flap system can further enhance the overall aerodynamic performance.

Sectional Lift Distributions on the Wing



- Both rotors reduces the sectional lift on the wing under the advancing side.
  - UH-60A rotor causes stronger aerodynamic interaction.
- Under the retreating side, the sectional aerodynamic performance of the wing with the opt-rotor reduces partially than with the UH-60A.
  - The induced velocity distribution from the rotor around the wing is different between the rotors.

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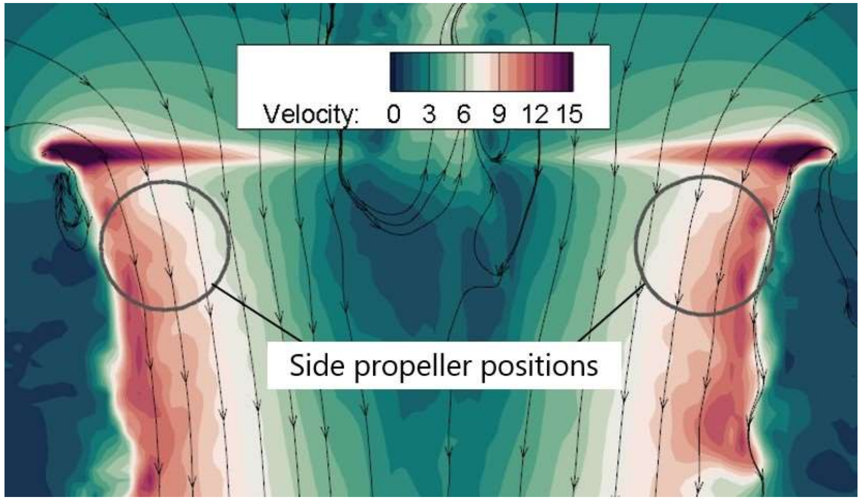
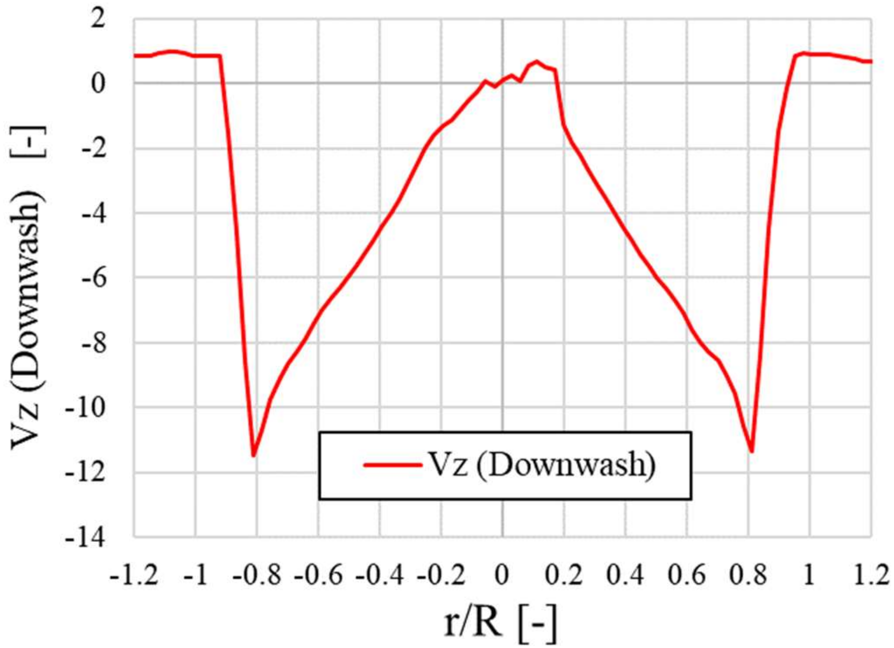
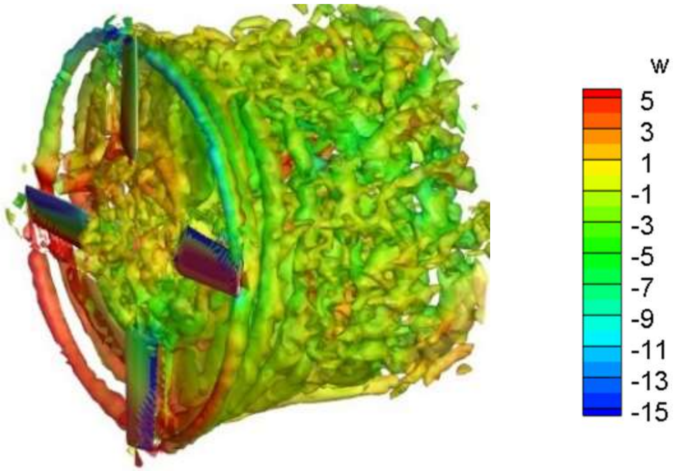
Rotor/Propeller Interaction

Downwash from the main rotor in hover

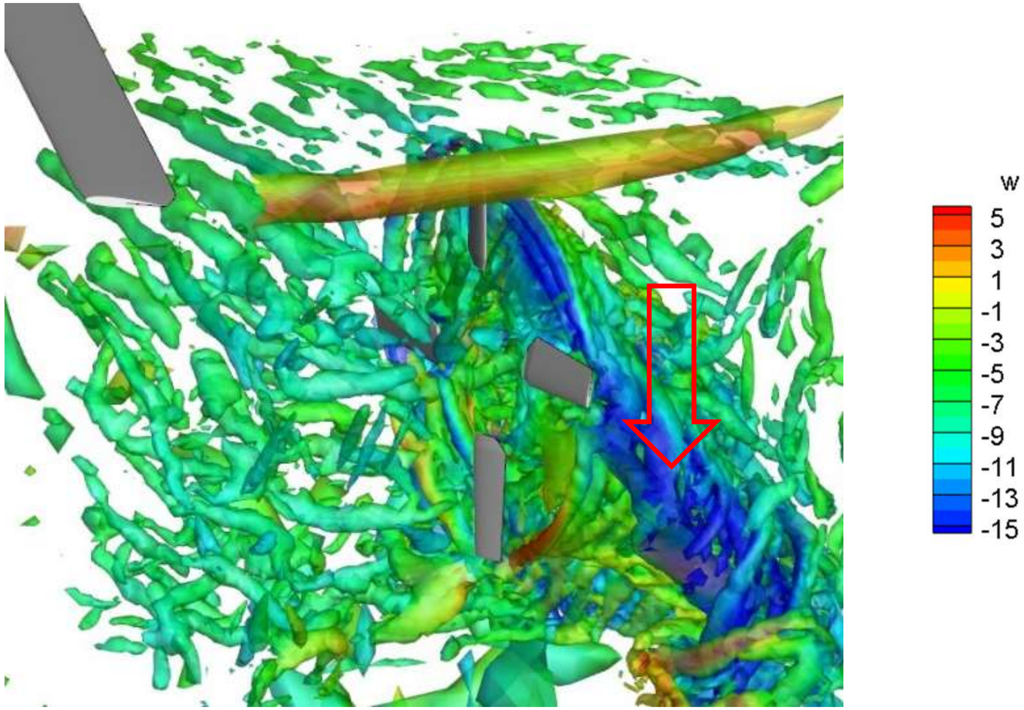




Flowfields of Rotor/Propeller Interaction



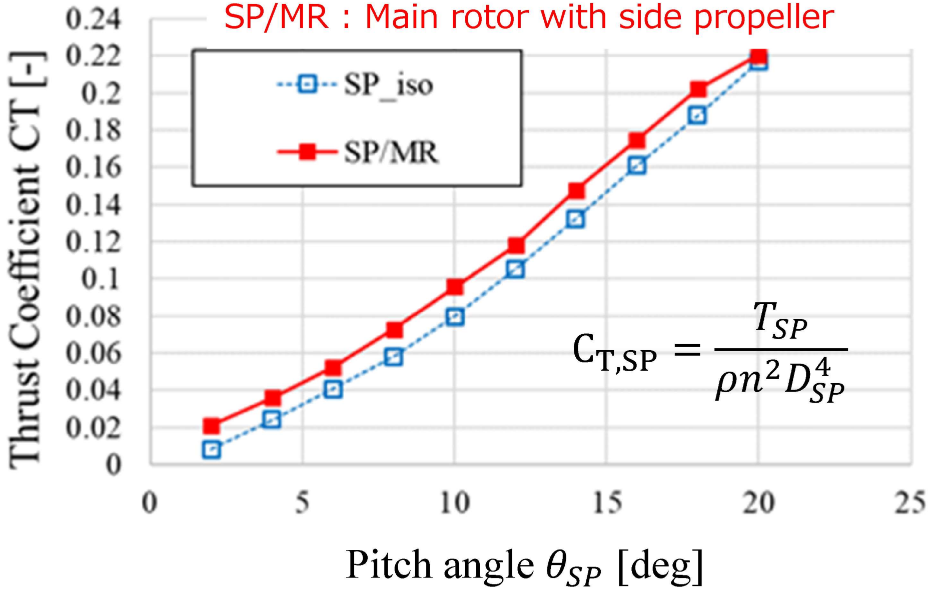
Isolated propeller



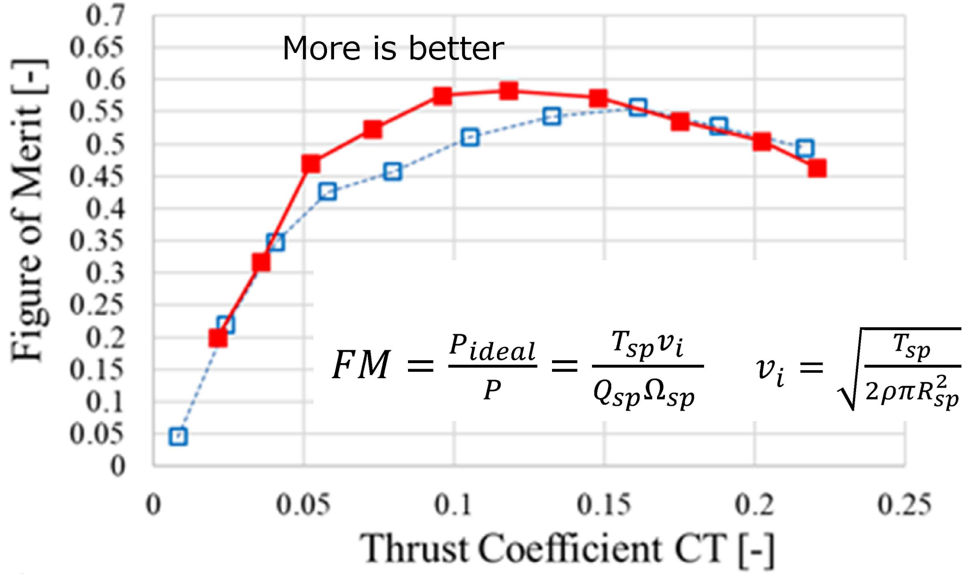
Rotor/Propeller Interaction

Performance of side propeller

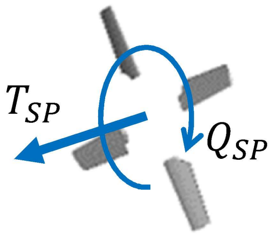
SP_iso : isolated side propeller
SP/MR : Main rotor with side propeller



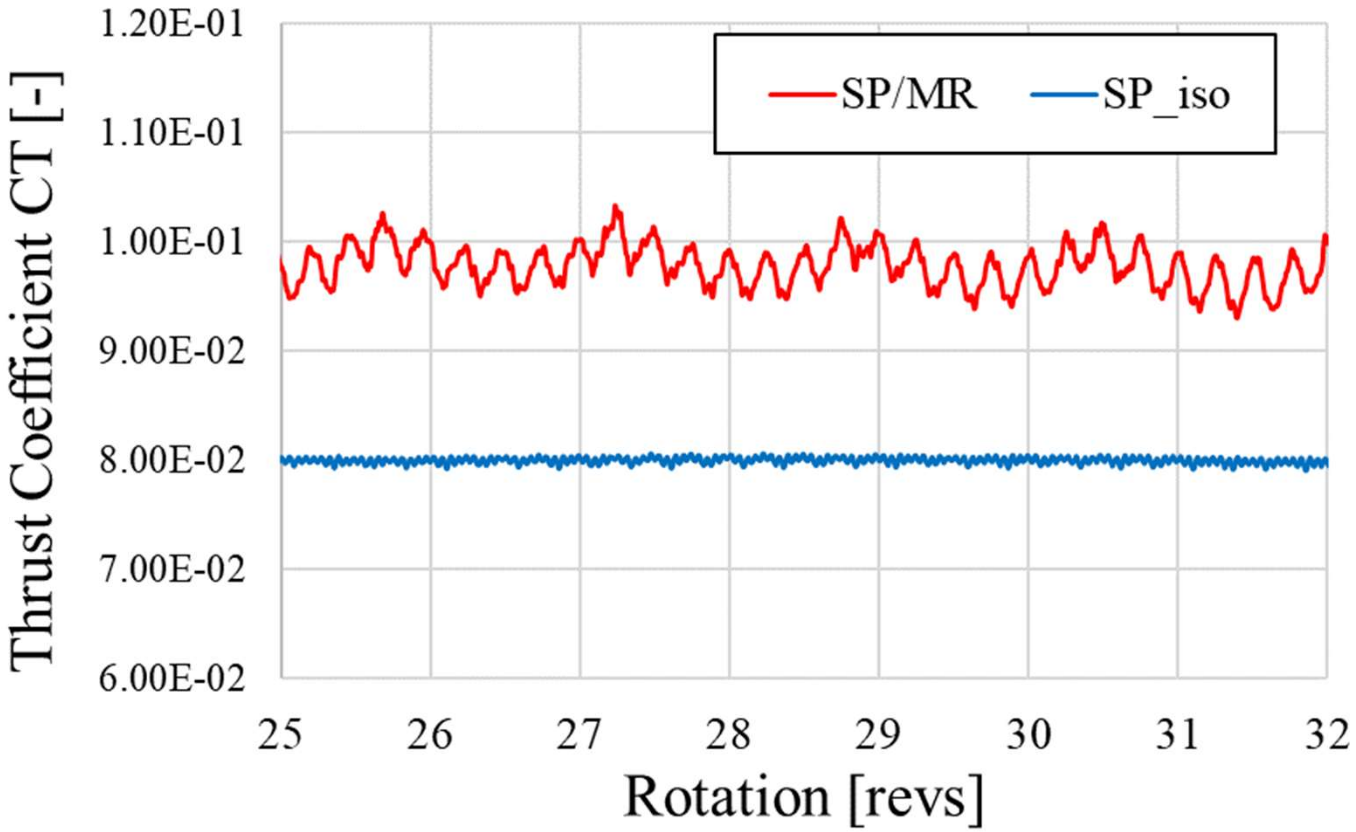
$$C_{T,SP} = \frac{T_{SP}}{\rho n^2 D_{SP}^4}$$



$$FM = \frac{P_{ideal}}{P} = \frac{T_{sp} v_i}{Q_{sp}\Omega_{sp}} \qquad v_i = \sqrt{\frac{T_{sp}}{2\rho\pi R_{sp}^2}}$$



Side propeller thrust fluctuations with/without the main rotor



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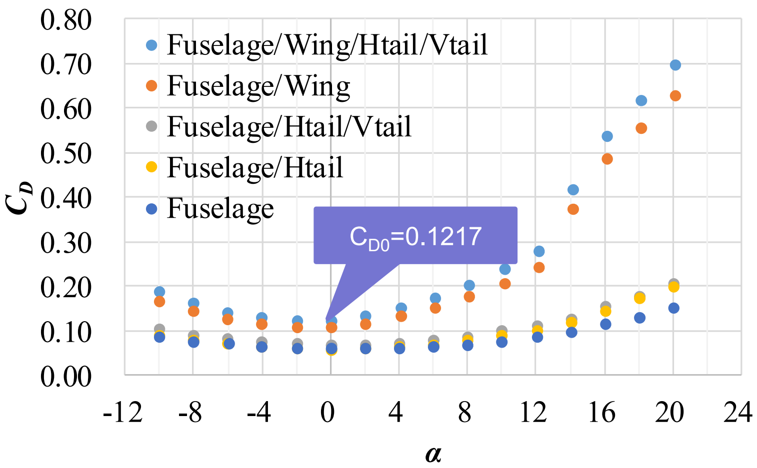
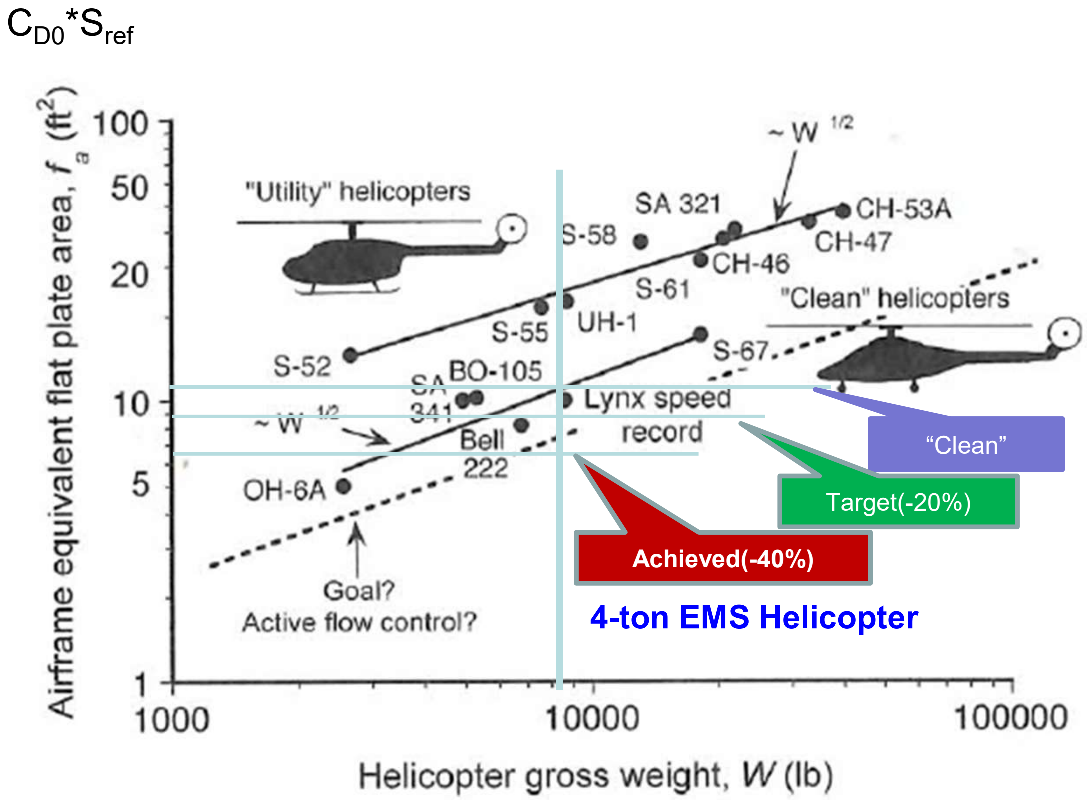
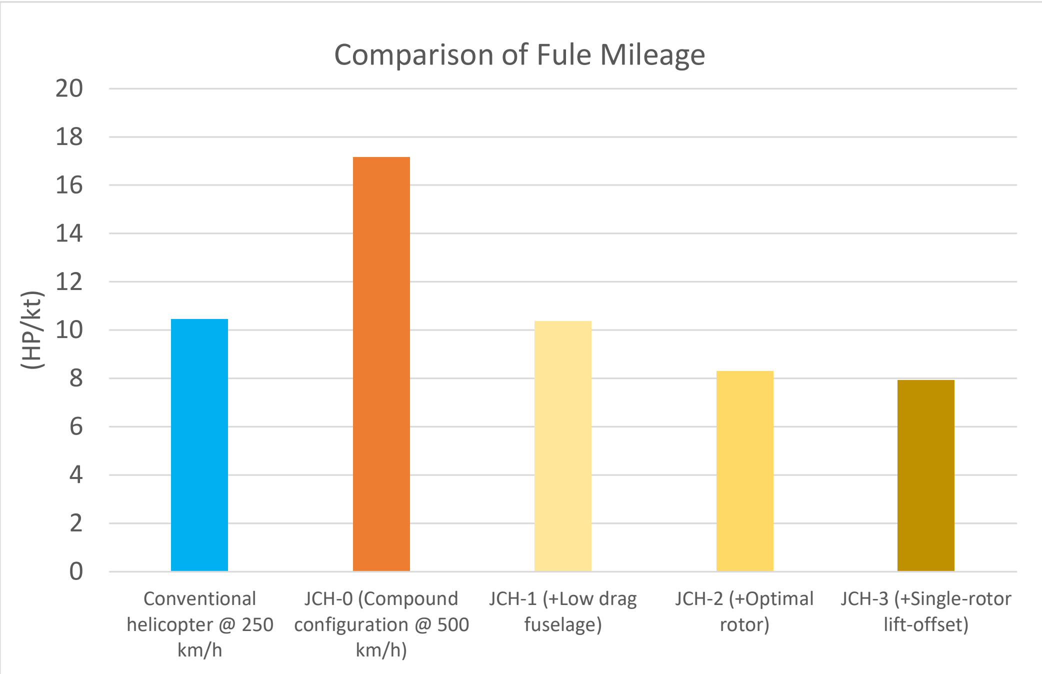
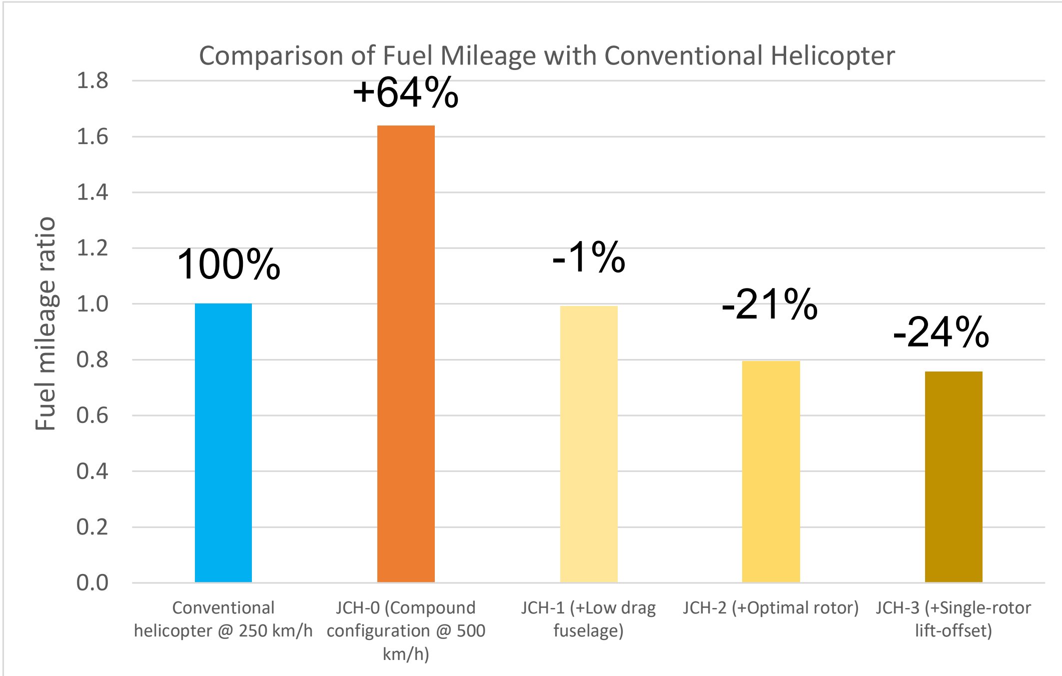
Low drag fuselage design





Realization of a high-efficiency compound helicopter through applying the advanced technologies

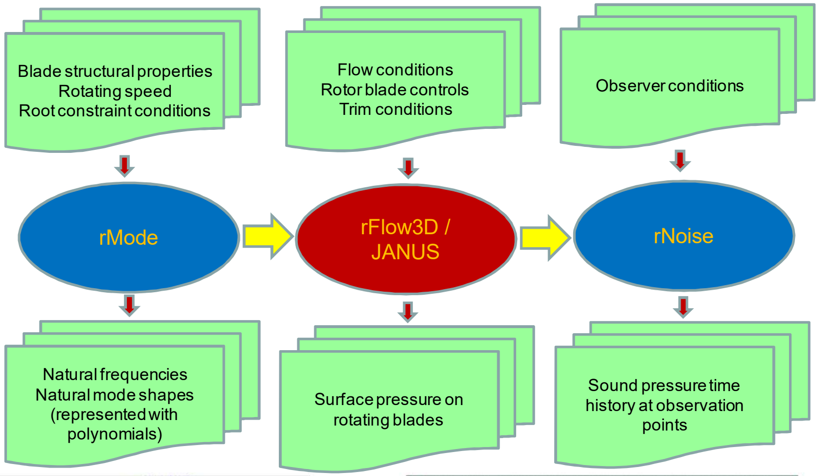


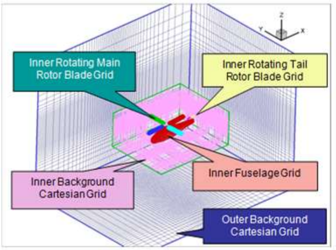


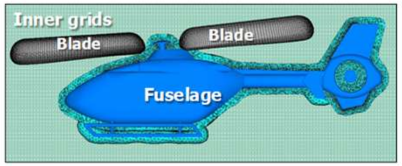
Comparison of fuel mileage with conventional helicopter

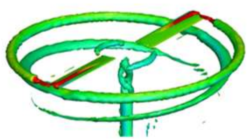
Spin-off Effects

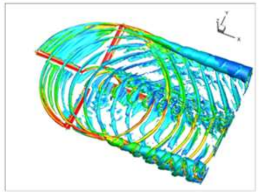
Numerical Analysis Flow

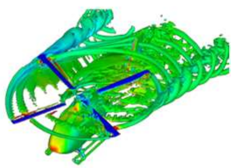




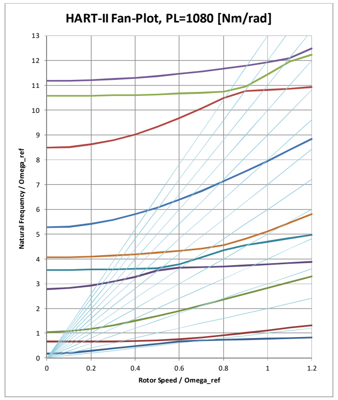




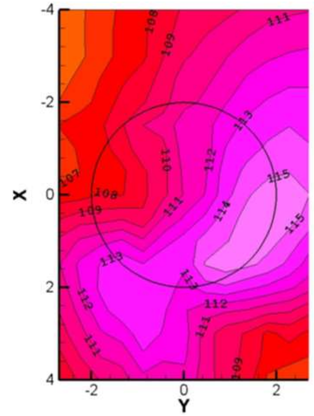




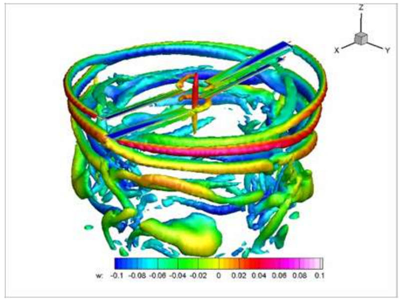
rFlow3D is being widely used for rotor analysis in Japan



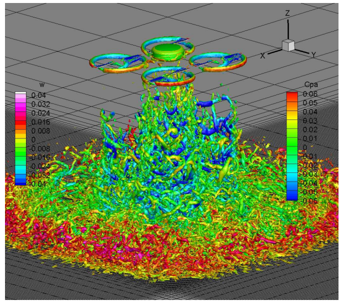
Fan-plot by rMode



BVI noise carpet by rNoise



Coaxial rotor



Quad-rotor in ground effect by rFlow3D

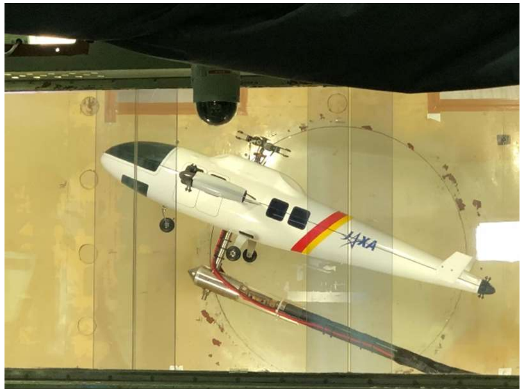
Summary

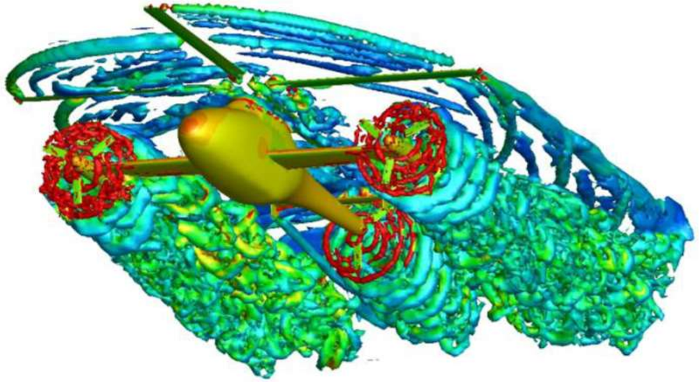
- A new concept of compound helicopter proposed by JAXA is illustrated. Technology issues related to the high-speed compound helicopter are addressed.
  - （1）Optimal design of rotor for high advance ratio flight
  - （2）Single-rotor lift-offset to improve the rotor performance in high-speed flight
  - （3） Rotor/propeller interaction
  - （4） Low drag fuselage design
- Through applying of the above advanced technologies, a high-efficiency compound helicopter can be realized where the flight speed is doubled while the fuel mileage can be kept the same or even less than the conventional helicopters.
- Spin-off effects of this research is introduced. The multi-disciplinary CFD/CSD/Trim/Noise prediction tool-chain (rFlow3D) developed alongside with this research has been applied to wind-turbines, multiple rotors, Mars helicopter and others.

Future Works

Optimal high-mu rotor design and other related technologies will be applied to a larger rotorcraft.

Thank you for your kind attentions!

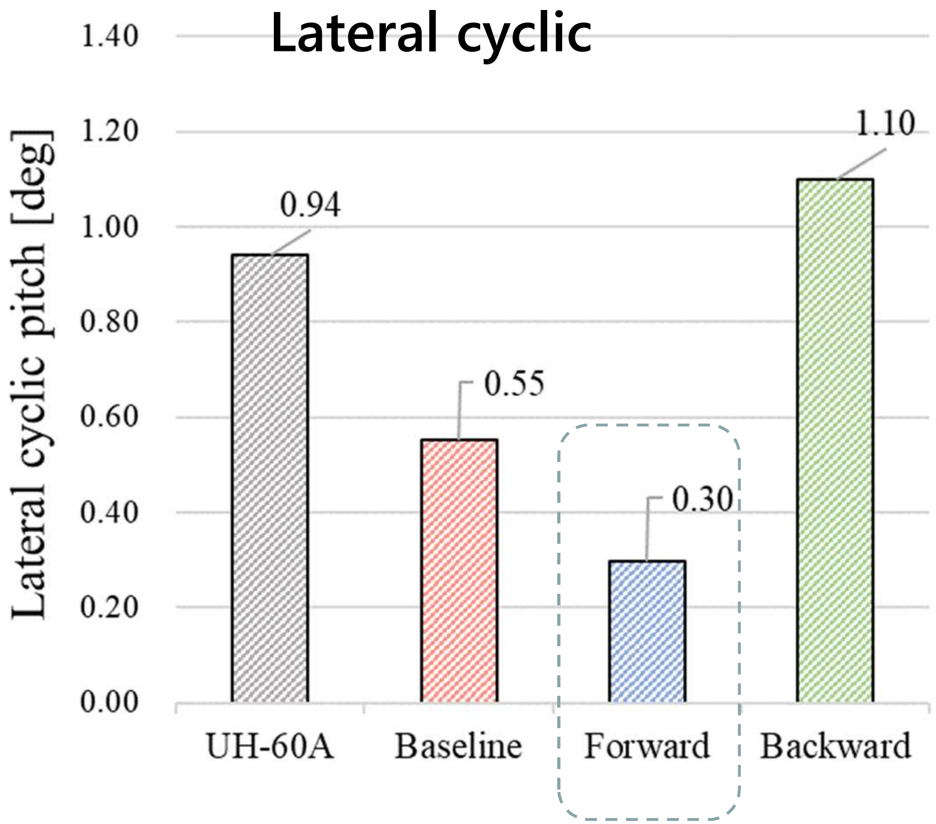


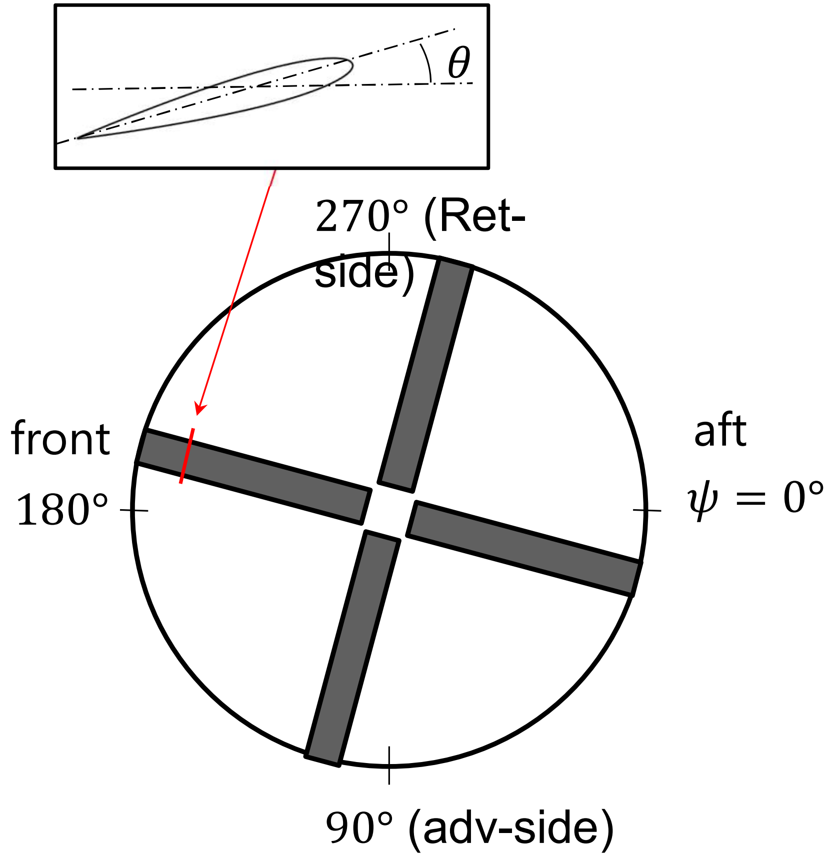


Appendix

Effect on cyclic pitch angle

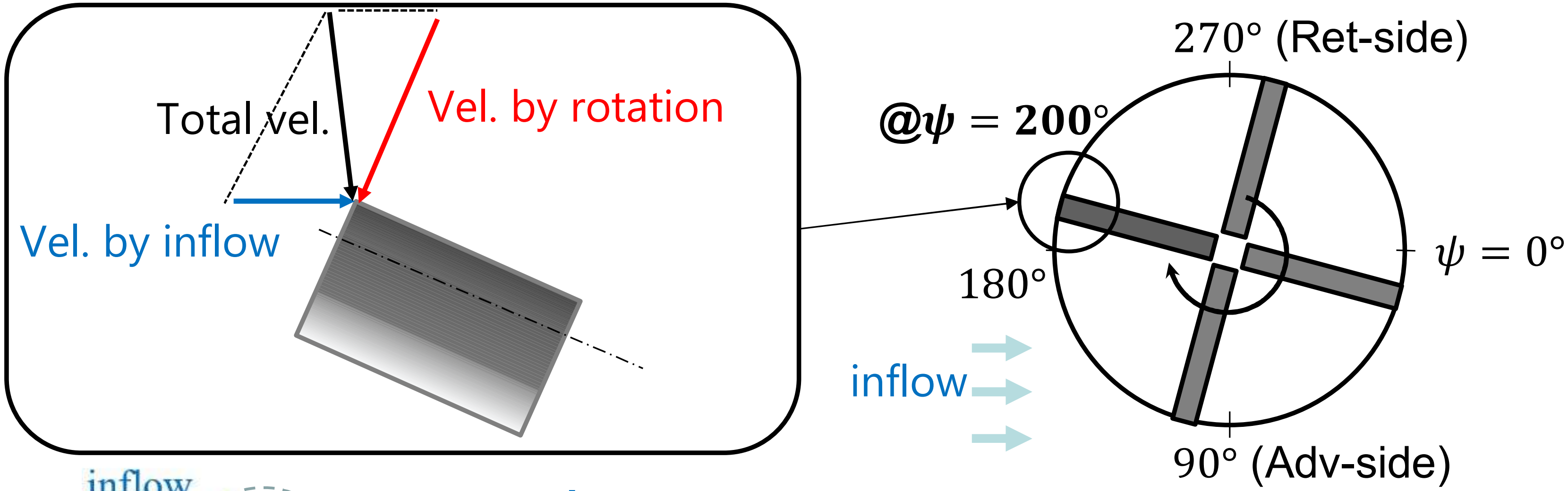
Pitch angle : $\theta = \theta_0 + \underline{\boldsymbol{\theta_{1c}}} \cos\psi + \theta_{1s} \sin\psi$

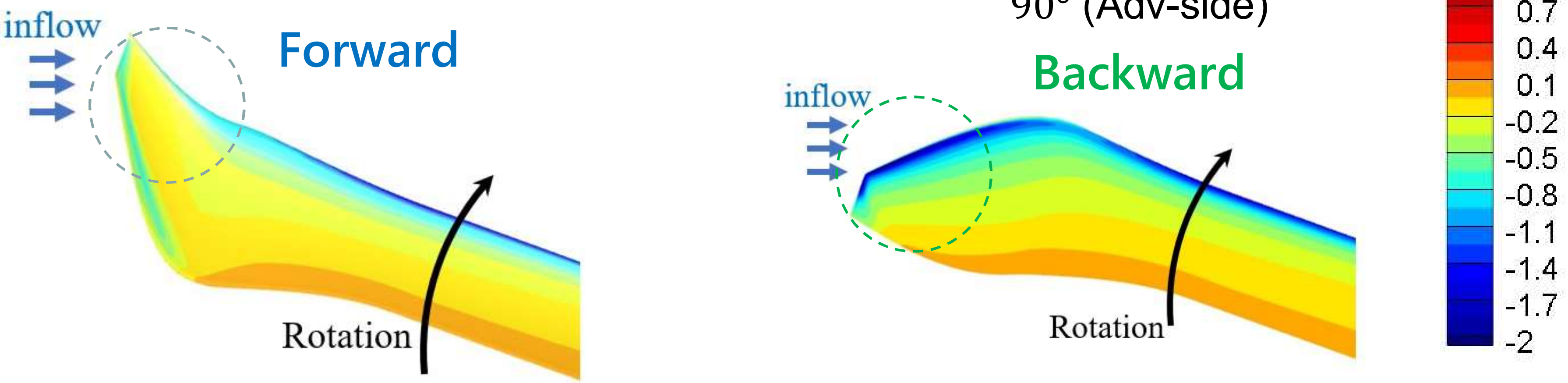




✓ lateral cyclic is smaller than other shapes ⇒ **more efficient AoA available!**

Sweep angle effect (Front-side)

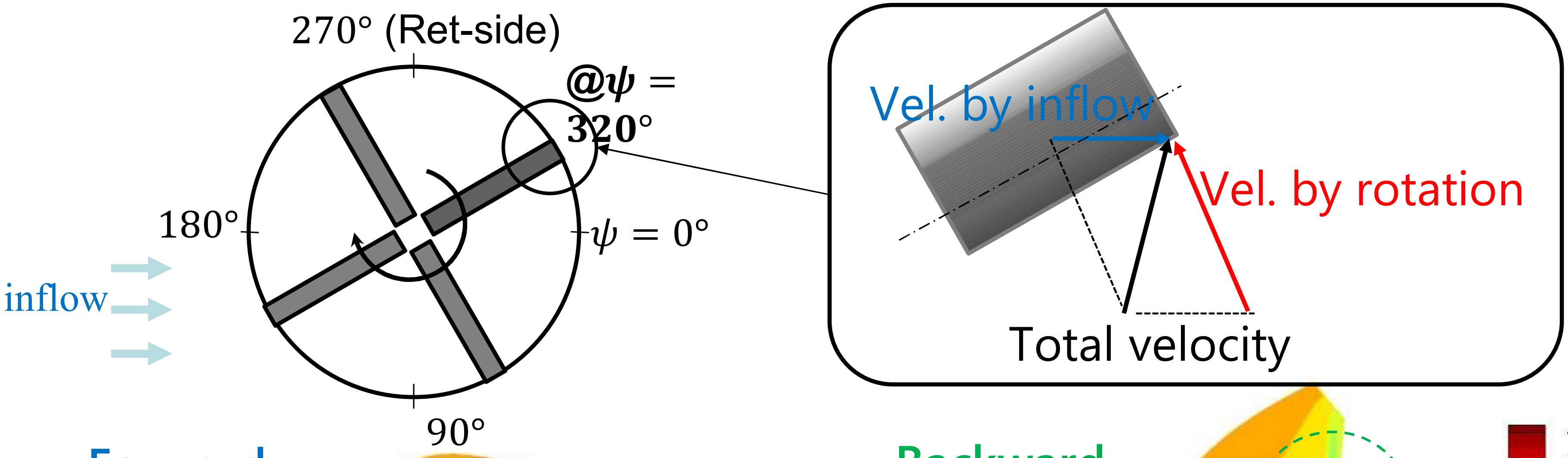




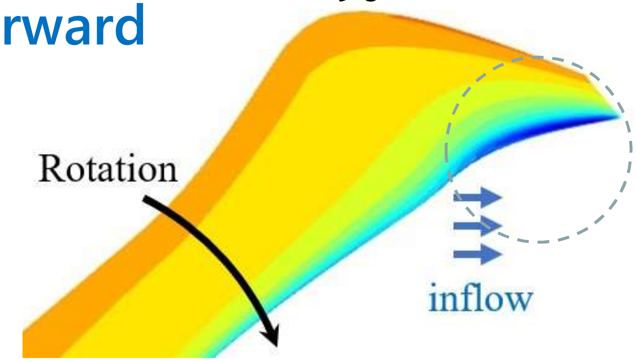
dynamic pressure@tip : Decreased

dynamic pressure@tip : increased

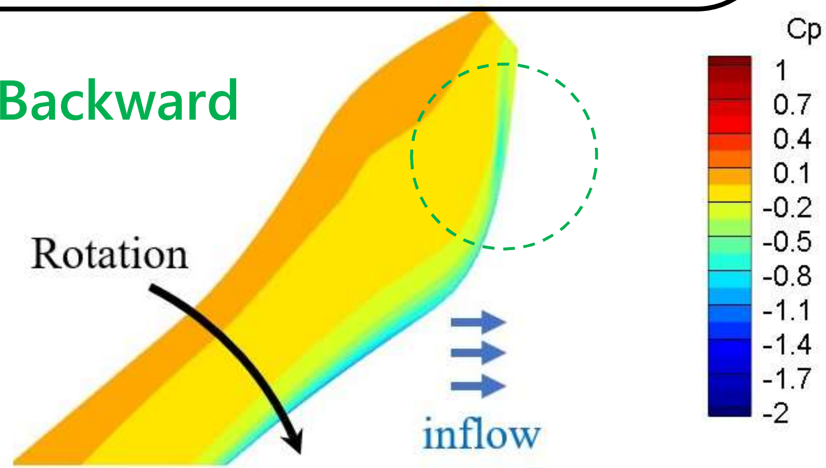
Sweep angle effect (aft-side)



Forward



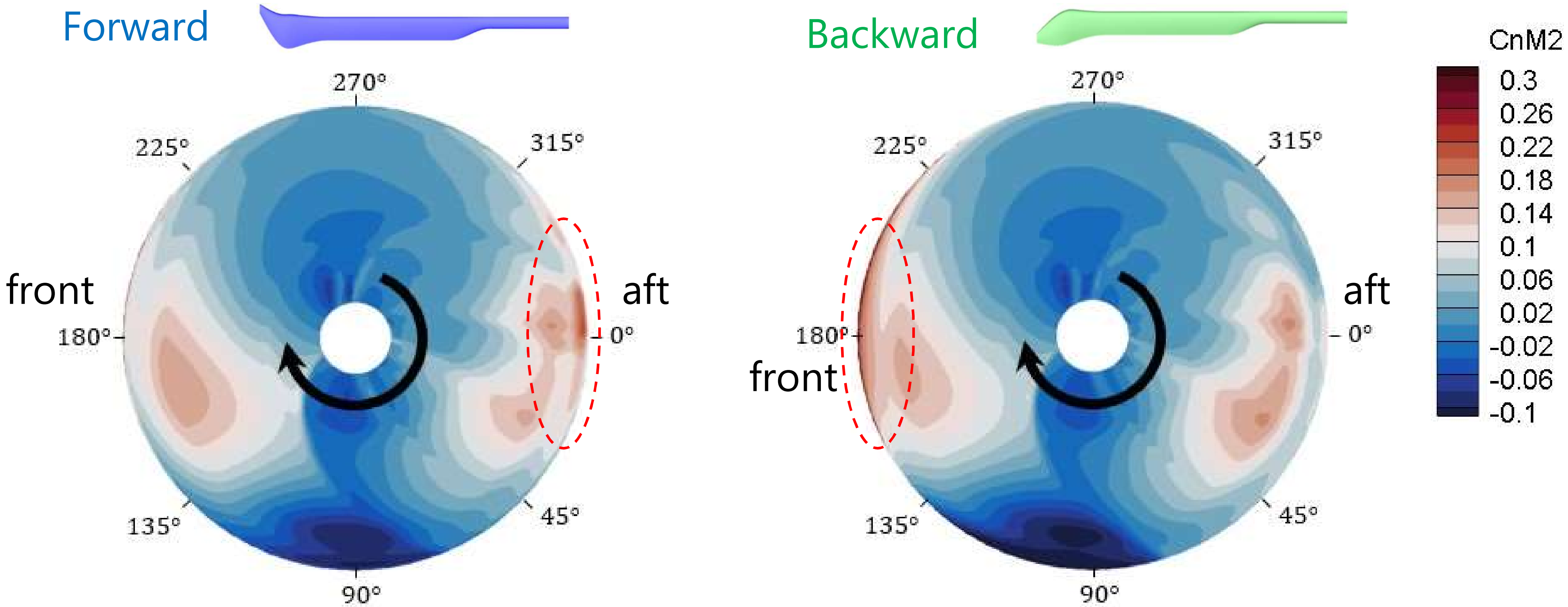
Backward



dynamic pressure@tip : Increased

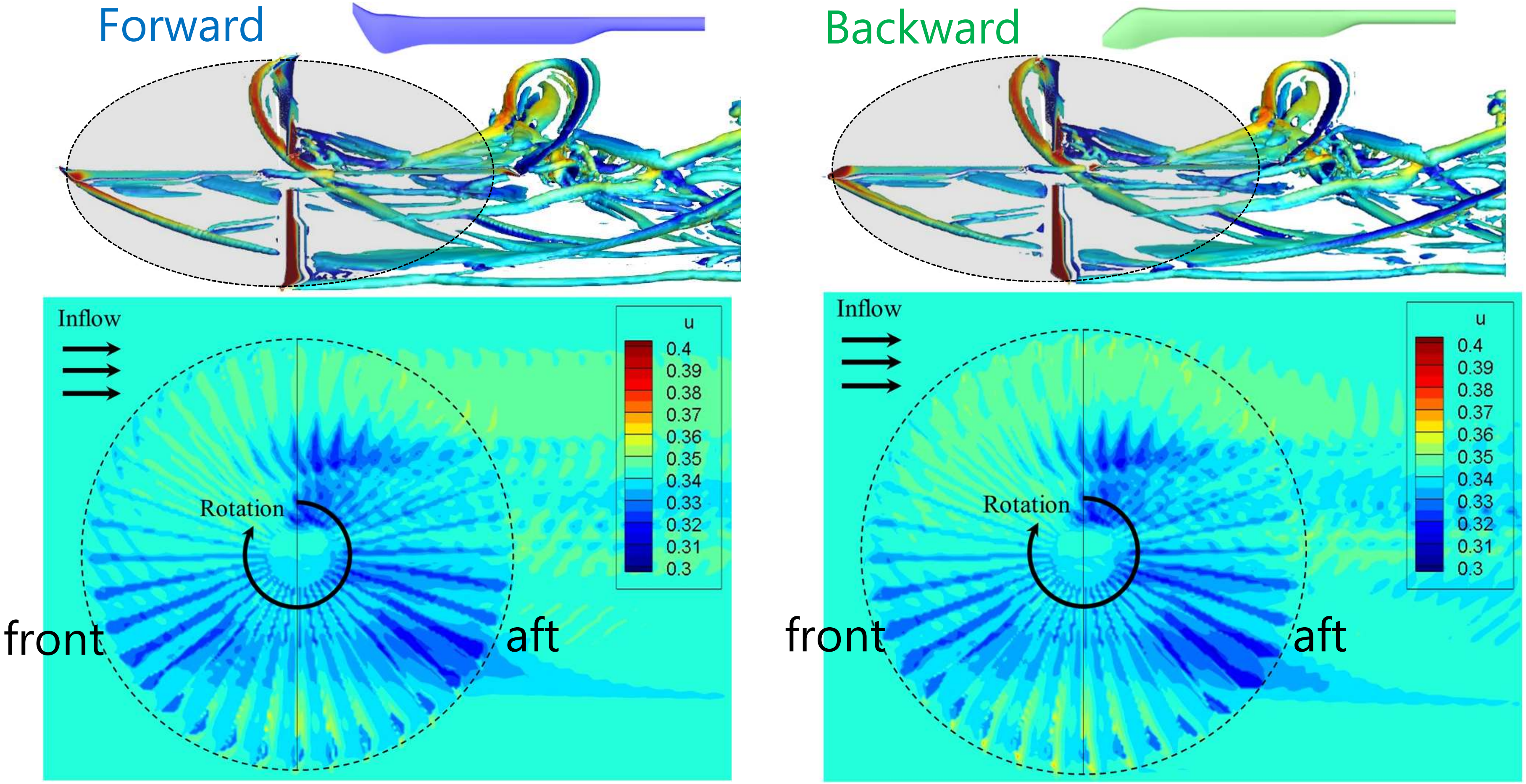
dynamic pressure@tip : Decreased

Lift distribution (CnM2)



- ✓ Forward : tend to generate more lift in aft-side
- ✓ Backward : more lift in front-side

Wake shadow effect

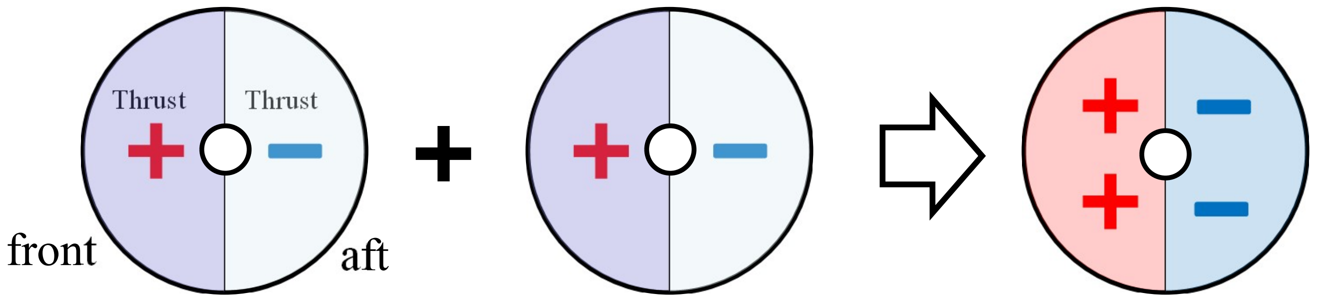


Wind speed : front-halt > aft-half ▶ Lift tends to be smaller in aft-side!

Total effect

Backward

(1)Backward sweep (2)Wake effect **Total**

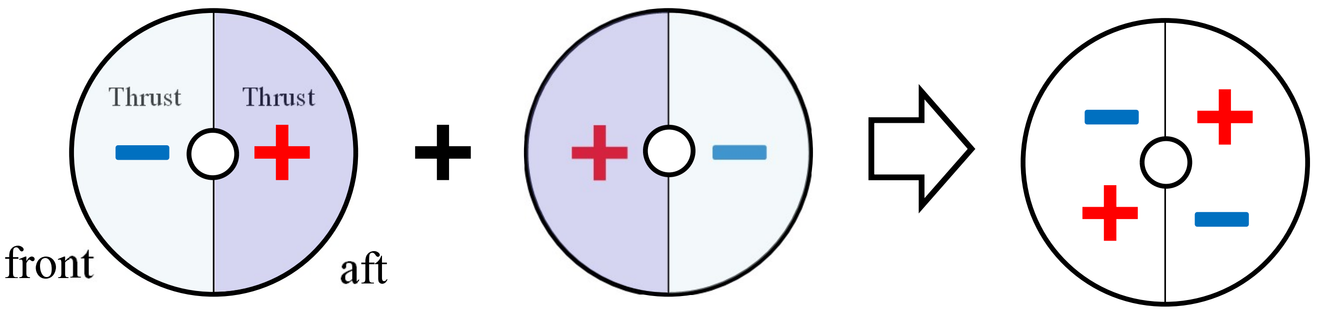


Unbalanced (→large θ_{1c})

Out of good AoA…

Forward

(1)Forward sweep (2)Wake effect **Total**



Balanced (→small θ_{1c})

Keep good AoA!