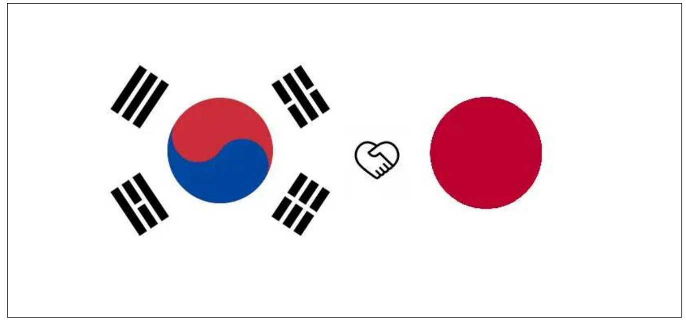
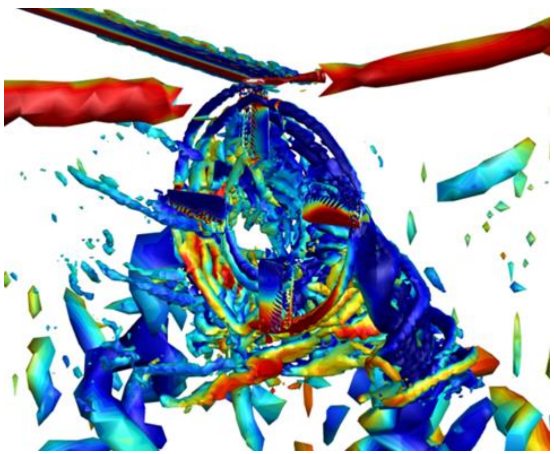
Japan-Korea Joint Workshop
on Rotorcraft
February 10, 2023, online



Simulation and design of propellers for a winged compound helicopter



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Topics

1. Introduction
2. Methodologies
3. Results Summary
   3-1 Side propeller
   3-2 Tail propeller
4. Concluding remark

Development of High-speed helicopter

Sikorsky Raider [1][2]

SB-1 DEFIANT [1][2]

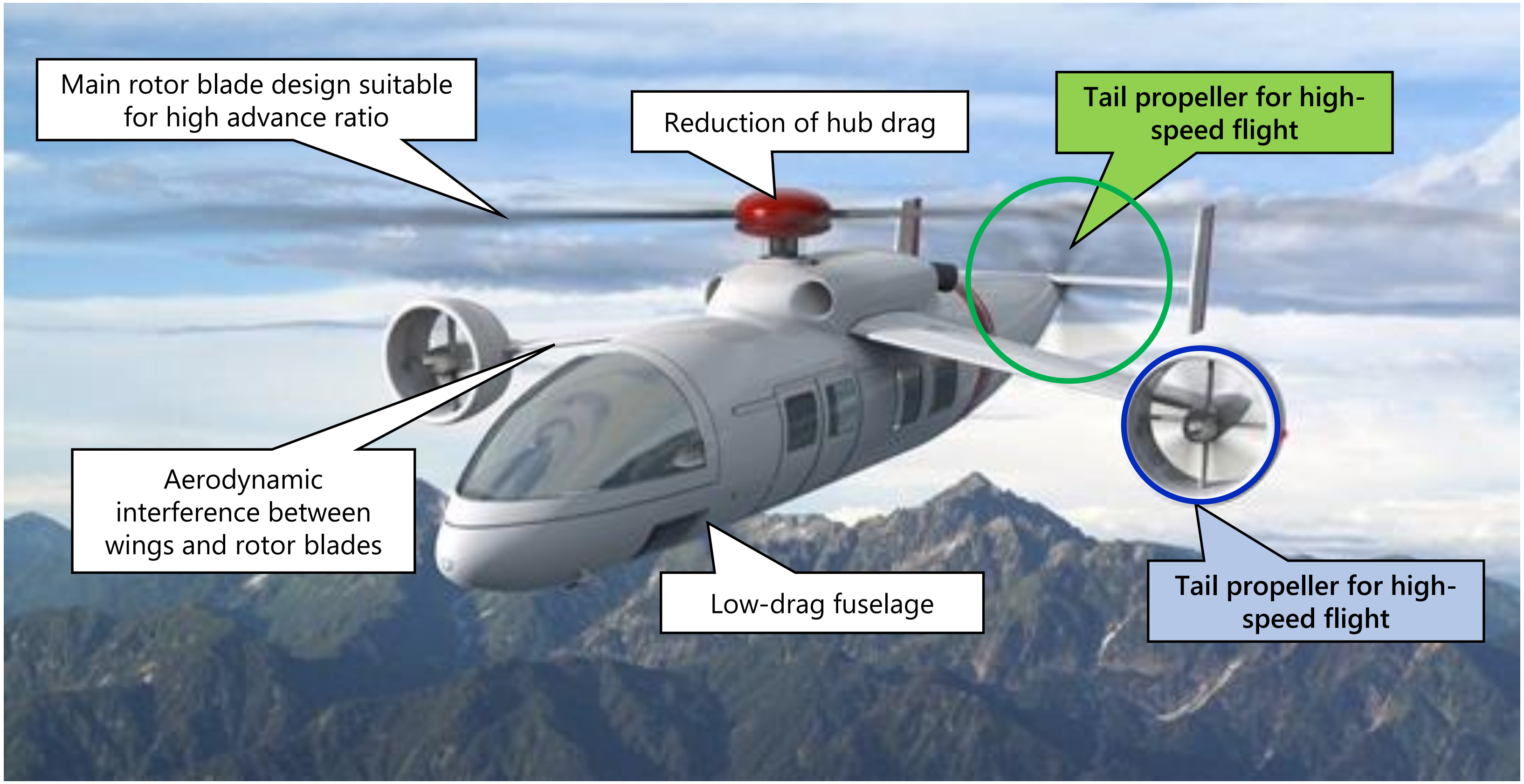
Airbus RACER[3]

JAXA conceptual compound helicopter [4]

- ✓ Compound helicopters with a fixed wing and propellers are promising way to higher speeds [1][2]
- ✓ In 2013, JAXA presented a concept for a compound helicopter that aims for a flight speed of 500km/h (fixed wing + side propellers + tail propellers)[4]

[1][2] "LOCKHEED MARTIN HP,“. [Online].
[3] Airbus, "Airbus Helicopters reveals Racer high-speed demonstrator," 20 6 2017. [Online].
[4] Y. Tanabe, et al, “A Conceptual Study of High Speed Rotorcraft,” 40th ERF, Southampton, UK, September, 2014.

Technical Issues



JAXA conceptual compound helicopter

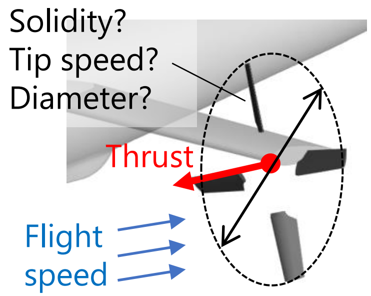
In this study, focus on <u>Side/Tail propeller design</u>

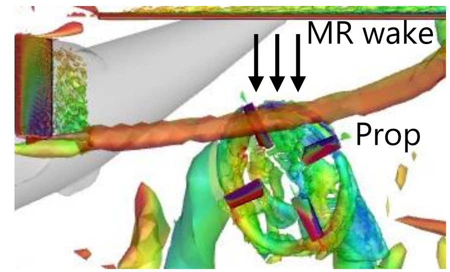
Overview for methodologies

Propeller design flow

(1) Conceptual Design Phase

- Set target condition
  (Flight speed, required thrust, size and so on)
- Research about aerodynamic interactions b/w Main rotor and/or fuselage
- Define design variables (N = 5~6)





Optimization start

convergence ?

Add new point(s)

No

Yes

Blade molding (1/7scale)

Initial sample points

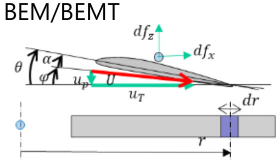
$$\vec{x}$$

$$\begin{pmatrix} x_{1,1} \\ x_{2,1} \\ x_{3,1} \end{pmatrix} \begin{pmatrix} x_{1,2} \\ x_{2,2} \\ x_{3,2} \end{pmatrix} \cdots \begin{pmatrix} x_{1,n} \\ x_{2,n} \\ x_{3,n} \end{pmatrix}$$

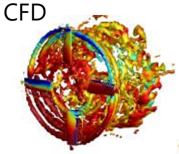
$x_{m,n}$: design variables

Low/high-fidelity simulations
Calculate objective function
$f(\vec{x})$

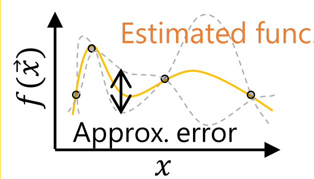
BEM/BEMT



CFD



Surrogate model
(Kriging + Expected Improvement)

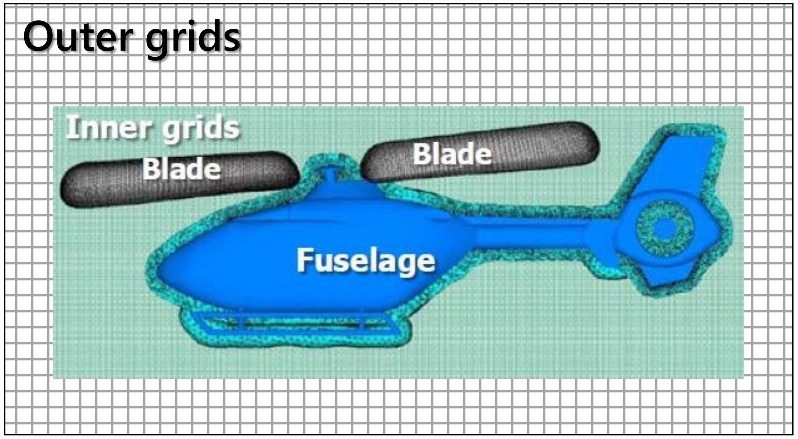


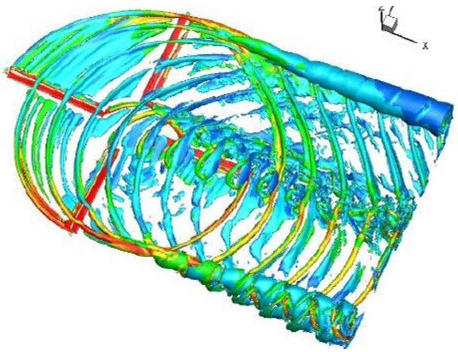
Propeller performance measured in wind tunnel

(2) Optimization Phase

(3) Evaluation Phase
(by wind tunnel test)

CFD solver : rFlow3D





Numerical methodologies in this study

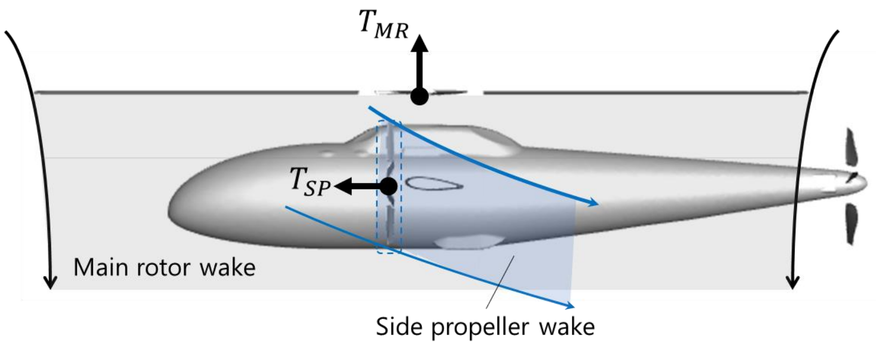
Governing equations	Three-dimensional compressible Navier-Stokes equations
Spatial discretization	Finite volume method
Time integration	4 stages Runge-Kutta (Background) Dual-time stepping, LU-SGS (Blade, Fuselage)
Viscous terms	2nd order central difference method
Reconstruction	Structured grid : FCMT (Fourth-order compact MUSCL TVD) [9] Unstructured grid : MUSCL+Green-Gauss with Hishida's limiter
Advection terms	mSLAU (modified SLAU)

- ✓ Moving overlapped grid method provides a direct representation of the rotor blade motion
- ✓ Trim analysis function can reproduce various flight conditions such as analysis with target thrust maintained

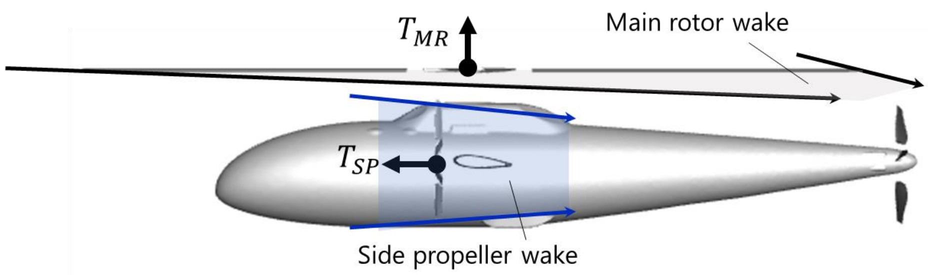
Side-propeller design note (1/2)

1. Aerodynamic interference with the downwash of the main rotor (especially when hovering)

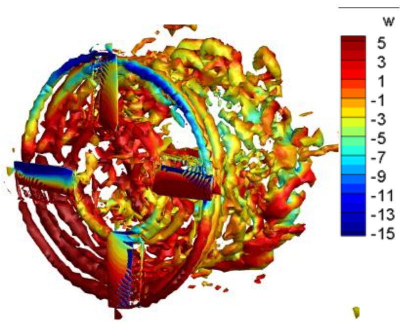
・**Hover** : having a major impact



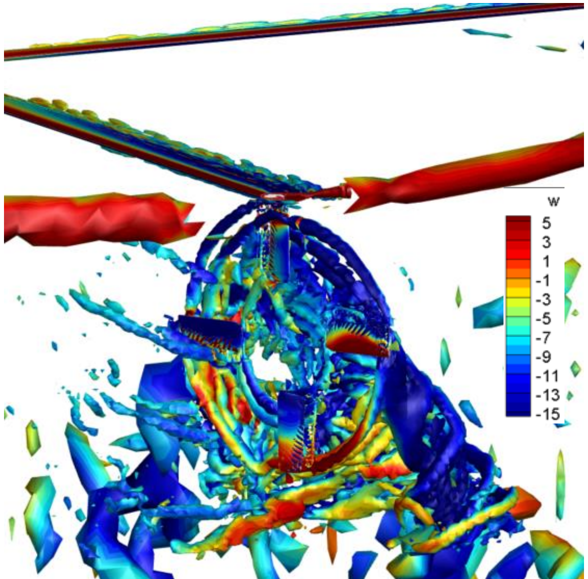
・**Cruise** : relatively small impact



Side propeller/ Main rotor interaction

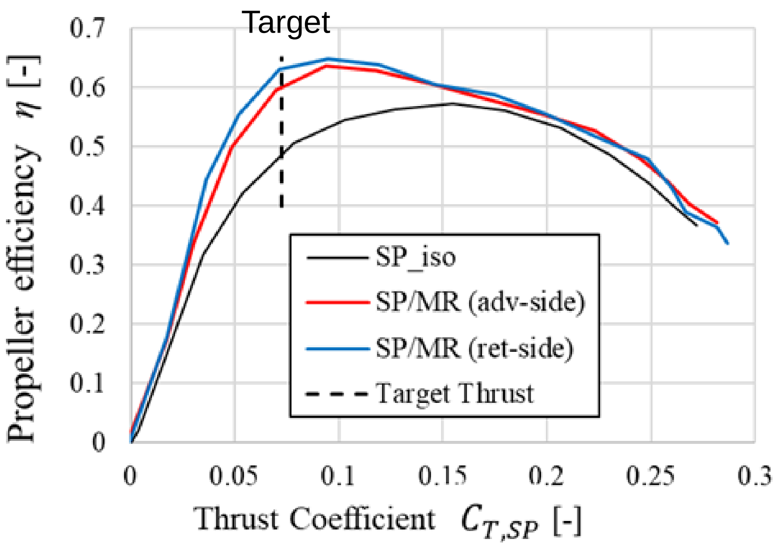


SP_iso
(isolated propeller)



SP/MR
(propeller/Main rotor interaction)

Flow visualization



Thrust - efficiency

- ✓ CFD analysis under isolated propeller (SP_iso) and interference condition (SP/MR)
- ✓ In hovering, thrust increase due to wake interference > improved performance

Verification of propeller performance

Contents before making it into Paper

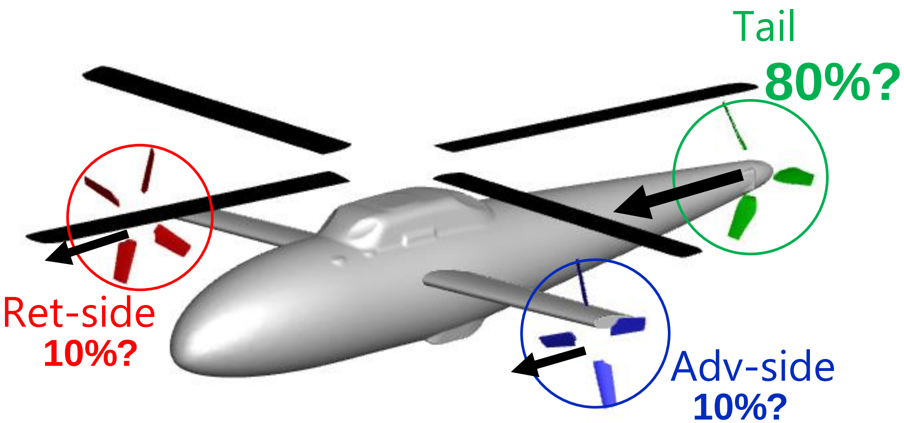
- ✓ Designed propeller made in 1/7 scale (RC helicopter scale)
- ✓ Wind tunnel test to confirm propeller performance
- ✓ Obtain Thrust/Torque to get propeller efficiency $\eta = \frac{TV}{Q\omega}$

⇒ <u>Confirmed significant performance improvement</u>

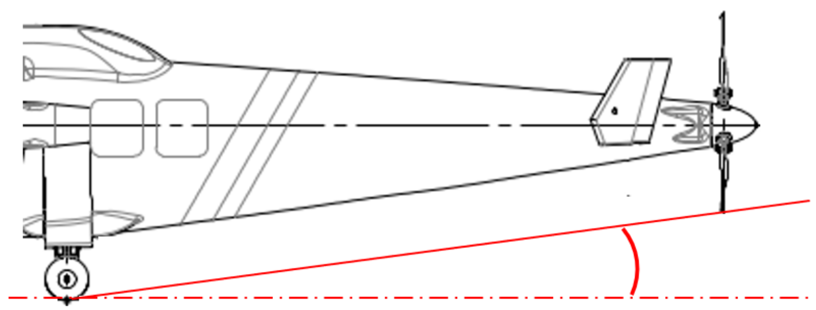
Difficulty in tail-propeller design

Points to note :

- ✓ Thrust large enough to balance fuselage drag at high flight speed (assuming 500 km/h)
- ✓ Thrust distribution between side props and tail prop (see figure)
- ✓ Aerodynamic interference with Main rotor/fuselage ?
- ✓ Sizing to avoid contact with the ground



Example of Thrust distribution
(different from the actual numbers)

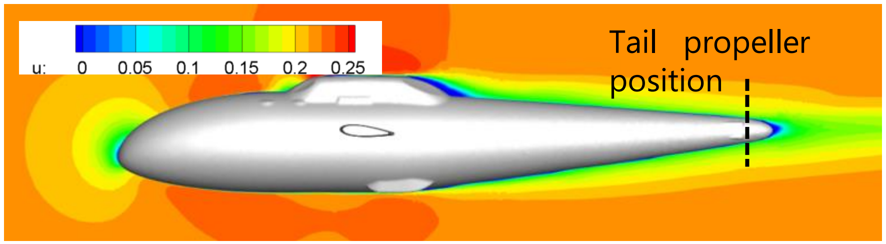


Some spacing between propeller and ground

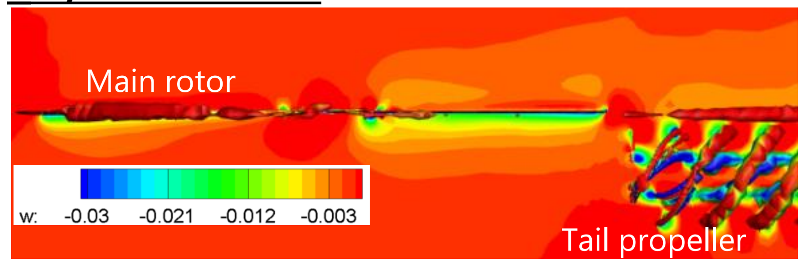
Aerodynamic Interactions

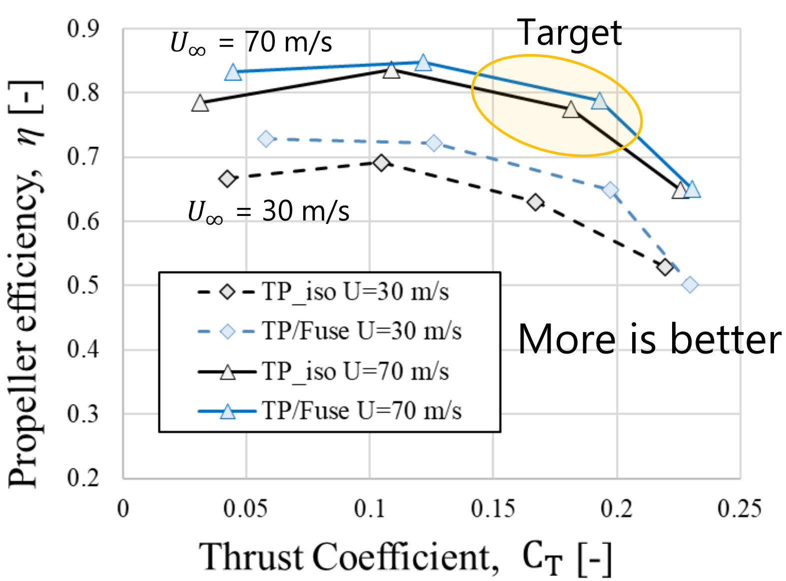
- ✓ 2 kinds of effects were investigated by using CFD
  - ✓ Fuselage/Tail propeller : positive effect on propeller efficiency
  - ✓ Main rotor/Tail propeller : small impact

・w/Fuselage

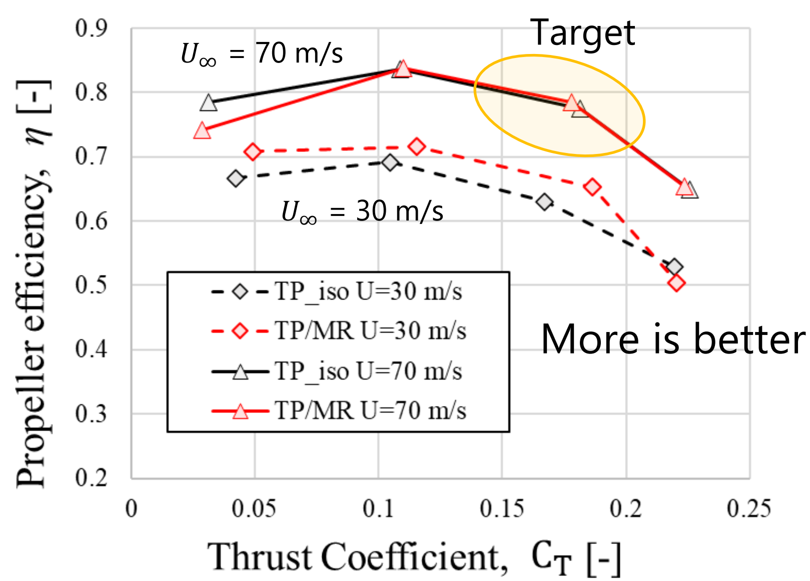


・w/Main rotor





Thrust – efficiency (w/&w/o Fuselage)



Thrust – efficiency (w/&w/o Main rotor)

Concluding remarks

An overview of JAXA's achivements on propeller design for high-speed compound helicopters is presented.

- **Side propeller**
  - ✓ CFD analysis confirms trend of increased thrust generated during hover (improved performance)
  - ✓ Presented a concept to enhance system performance by applying different shapes on the Adv-side and Ret-side propellers.

- **Tail propeller**
  - ✓ Confirm the effect of interference between the fuselage and the main rotor (Positive effect by fuselage interaction)
  - ✓ Propeller design for Full-scale application. Appropriate solidity and shape were obtained.

- **Future works**

  Flight test with RC helicopter equipped with opt-propellers to demonstrate performance improvement

Thank you for your kind attention!