JAXA-ONERA-DLR COOPERATION: RESULTS FROM ROTOR OPTIMIZATION IN FORWARD FLIGHT

Keita Kimura (JAXA)
Gunther Wilke (DLR)
Joëlle Bailly (ONERA)
Yasutada Tanabe (JAXA)

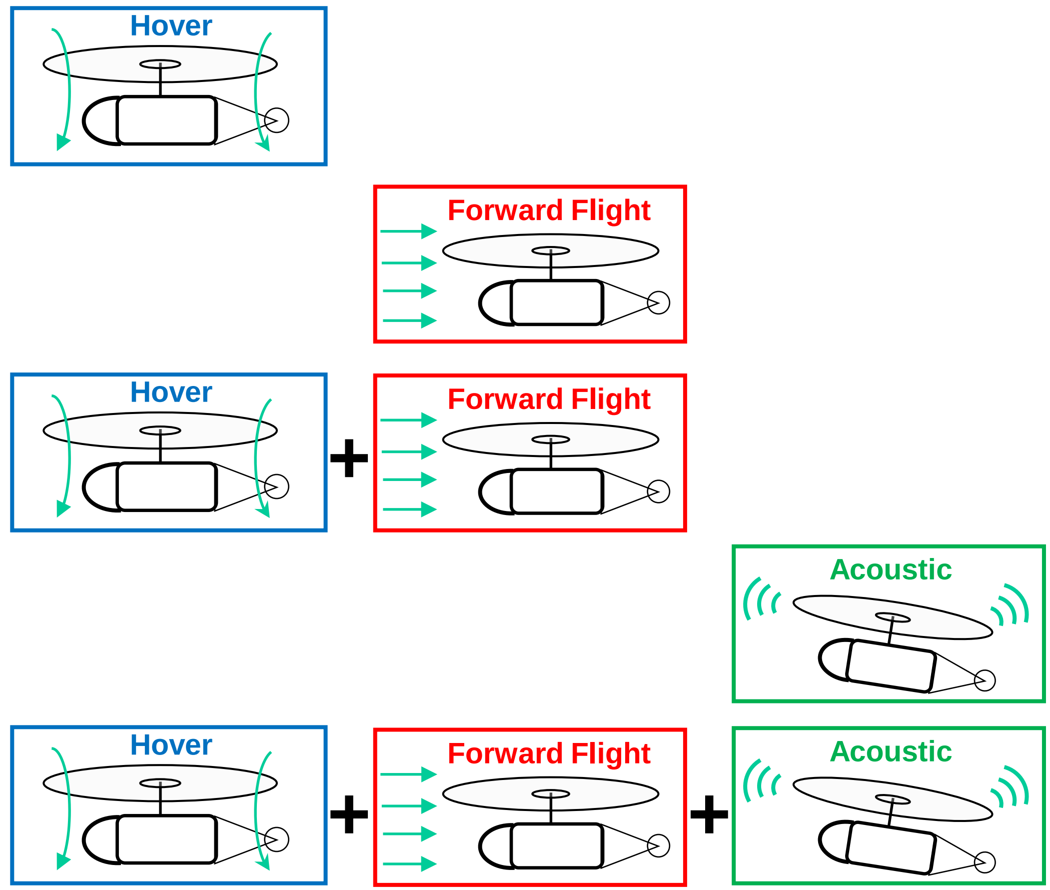
Topics

1. Intro
2. Methodologies
   - solvers (Low-fidelity/High-fidelity)
   - optimization settings
3. Results
   - Baseline blade simulation
   - obtained optimal shapes
4. Discussion
   - aerodynamic distribution
5. Concluding remarks

Introduction

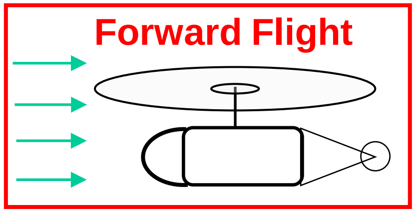
- ✓ Trilateral study b/w JAXA/ONERA/DLR for rotor blade optimization
- ✓ Cross-validation of solvers and optimization tools b/w partners is one of the main objectives

WP1. Optimization in Hover
WP2. Optimization in Forward Flight (This paper)
WP3. Multi-point optimization in Hover + Forward Flight
WP4. Acoustic Optimization
WP5. Multi-objective Optimization in Hover+Forward+Acoustic



Introduction

○WP2 : Optimization in Forward Flight



- ✓ **Goal** : To obtain guidelines for blade design (plane shape and torsion angle) suitable for high-speed forward flight
- ✓ In recent years, compound helicopters with a fixed wing and/or propellers are promising way to higher speeds
  ⇒ Optimal design under <u>high advance ratio conditions</u>

Sikorsky Raider [1][2]

Airbus RACER[3]

[1][2] "LOCKHEED MARTIN HP,“. [Online]. [3] Airbus, "Airbus Helicopters reveals Racer high-speed demonstrator," 20 6 2017. [Online].

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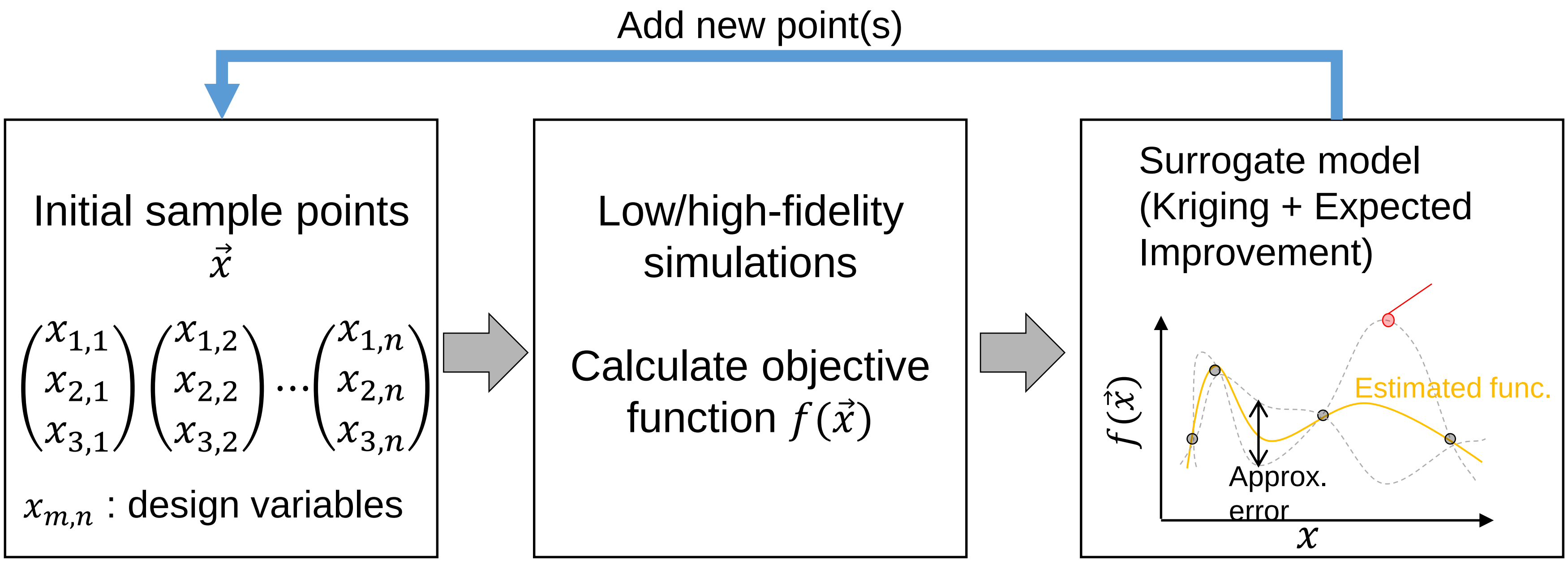
Optimization methodologies

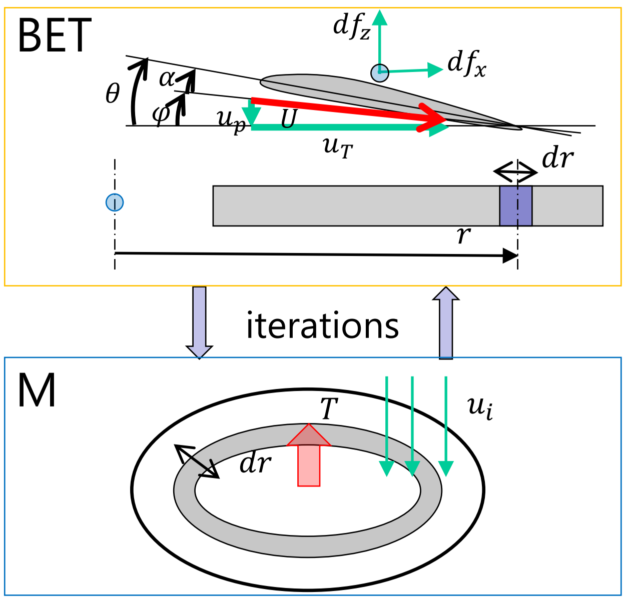


- ✓ Using surrogate model to reduce the # of points to be calculated
- ✓ Low/high-fidelity simulation tools and optimizers have been developed in each agency

Solvers - Low-fidelity methods -

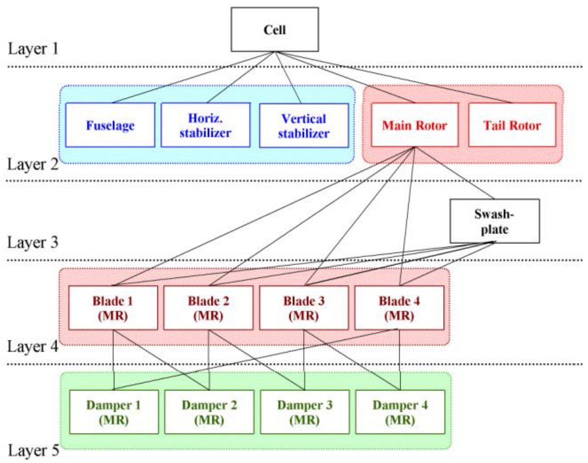
JAXA：rBET

- ✓ In-house code for simple analysis of rotor based on Blade Element Theory (BEM) + momentum theory = (BEMT)
- ✓ Assume Rigid blade
- ✓ Use Linear inflow model



DLR & ONERA：HOST

- ✓ Comprehensive analysis code developed by Airbus helicopter
- ✓ each component are individually modeled
- ✓ Assume elastic blade of slender beam
- ✓ Available aerodynamic/structural analysis
- ✓ Use prescribed wake model



Analysis tree of Host

Solvers - High-fidelity methods -

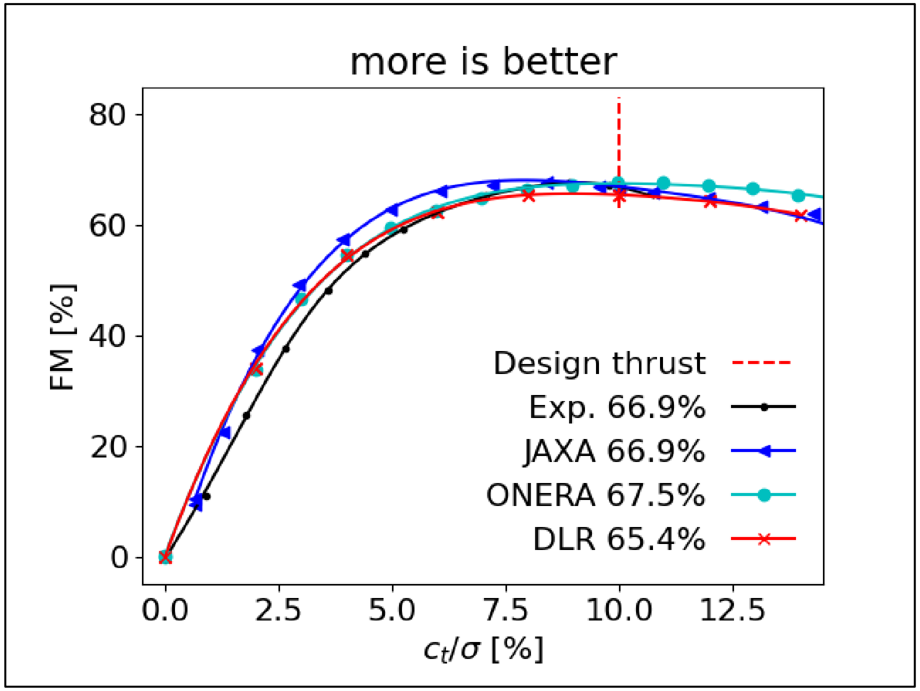
- ✓ All partners apply unsteady RANS(Reynolds averaged Navier-Stokes) simulation

CFD methods of each agency

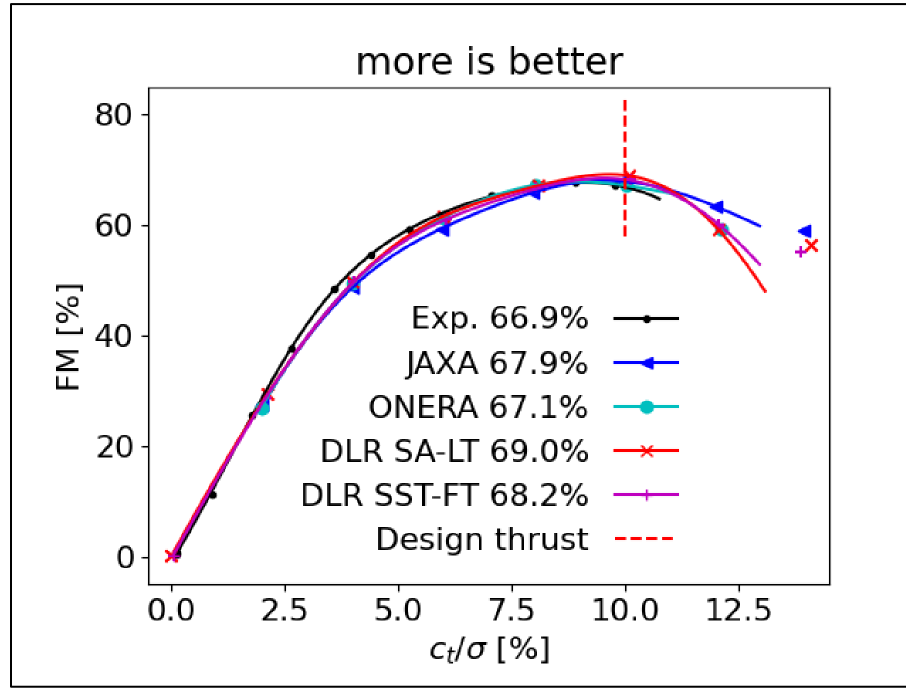
	JAXA	ONERA	DLR
solver	rFlow3D	elsA	FLOWer
Inviscid scheme	4^{th}order FMCT+SLAU2	2^{nd} order JST	4^{th} order FMCT (vA) +SLAU2
	with 2^{nd} order finite volume metrics		
Time integration	Dual time LU-SGS (Blade) & 4 stage RK (Background)	Dual time Backward Euler scheme + LU-SSOR	Dual time Backward Euler scheme + LU-SGS
Turb. model	SA-R Fully turbulent	Kok-SST Fully turbulent	SA-DDES-R + empirical transition
Rotor property	Rigid	Elastic, through delta airloads approach with HOST	

Cross-validation for solvers

WP1's results – Figure of Merit Polars



Low-Fidelity
(JAXA : rBET, ONERA : HOST, DLR : HOST)

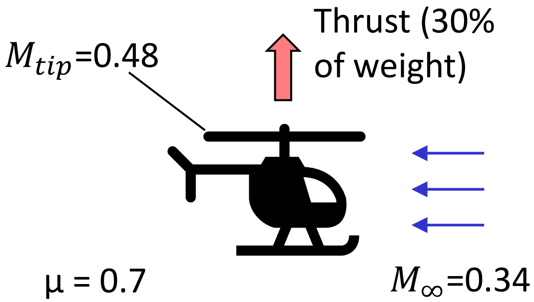


High-Fidelity
(JAXA : rFlow3D, ONERA : elsA, DLR : FLOWer)

✓ Cross-validation between solvers has been completed during previous optimization studies (WP1, hover condition) [4]

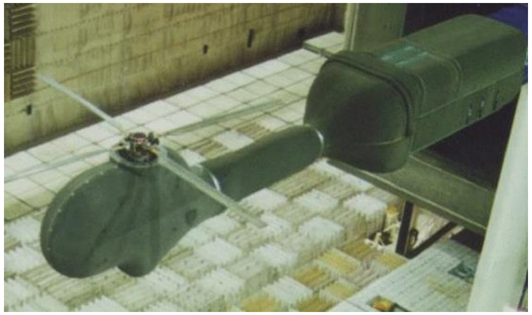
[4] G. Wilke, J. Bailly, K. Kimura , Y. Tanabe, "JAXA-ONERA-DLR cooperation:results from rotor optimization in hover," CEAS Aeronautical Journal, 13(2), 313-333, 2021

Target condition & Reference blade



Flight condition for optimization

item	value
Thrust	1080 N (30% of weight)
CT/σ	0.034 (σ=0.077)
Advance ratio μ	0.7 (= M_∞/M_{tip}= 0.34/0.48)
Rotational speed	781.5 [RPM] (75% slowed rotor)



HART II rotor configuration (From [5])

Baseline blade (HARTII blade [5])

Number of blades	4
Radius R [m]	2.0
Chord length c_{ref} [m]	0.121
Linear-nose down twist	-8 [deg]
Blade shape	Rectangular
Airfoil	Modified NACA23012

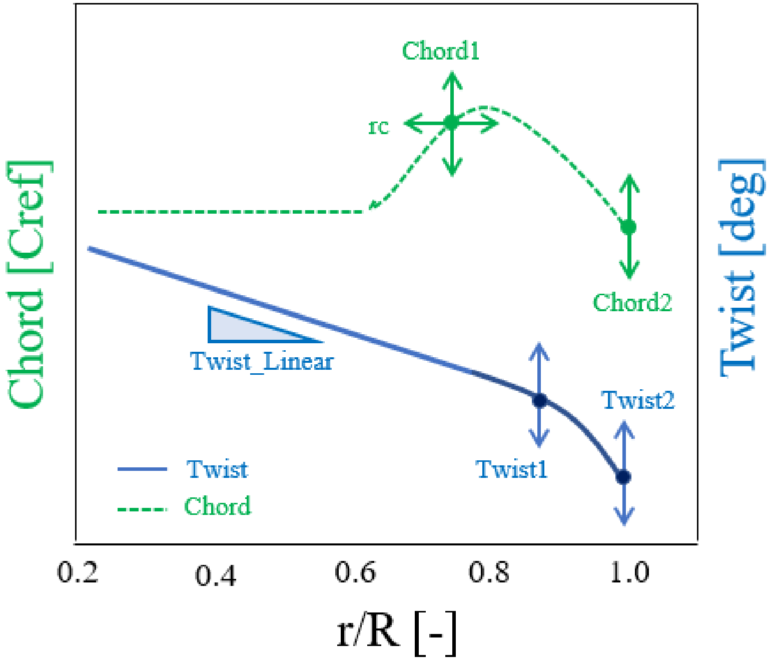
- ✓ Baseline blade specifications are based on the HARTII test (Bo105 40% down-scaled model conducted at DNW)
- ✓ To achieve high advance ratio, rotational speed is slowed down to 75% and the lift share to 30%.

P. M. Küfmann, R. Bartels, B. G. Van_Der_Wall, O. Schneider, H. Holthusen and J. Gomes, "The first wind tunnel test of the multiple swashplate system: tesdure and principal results," Journal of the American Helicopter Society 62.4 (2017): 1-13., 2017.

Design Variables

Design variables

Name	Variables setting	Range
Twist1	dθ1 @r/R = 0.875	-5° ~5°
Twist2	dθ2 @r/R = 1.0	-5° ~5°
Twist Linear	Linear nose down twist from root to tip	-10° ~0°
rc	control section for chord1	0.5R~0.85R
Chord1	Chord @rc	1.0~1.5Cref
Chord2	Chord @r/R = 1.0	0.5~1.0Cref

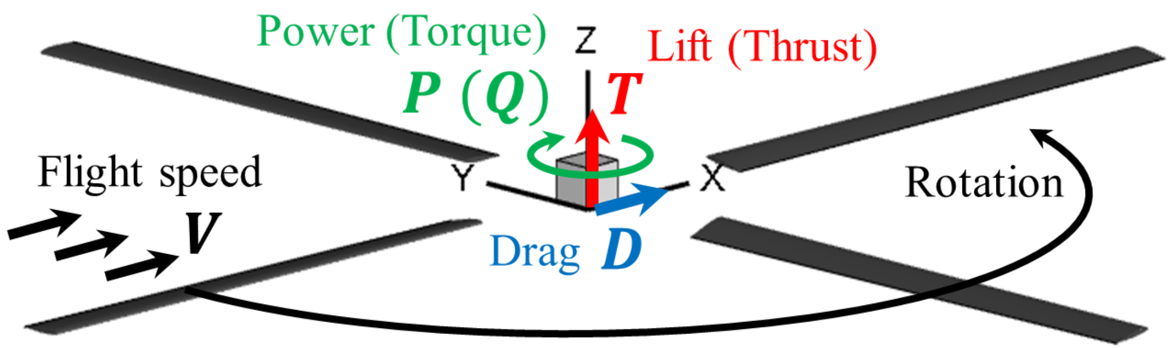


Sketch of design variables

- ✓ 6 design variables to change planform and twist of the blade (2 chord, 3 twist, 1 control point)
- ✓ Cubic spline interpolation is applied to get whole distribution

Objective Function

Evaluated by effective lift-drag ratio L/D_e



$$L/D_e = \frac{C_T}{C_{De}} = \frac{C_T}{C_D + C_Q/\mu} \qquad C_T = \frac{L}{\rho A V_{tip}^2} \quad C_D = \frac{D}{\rho A V_{tip}^2} \quad C_Q = \frac{Q}{\rho A V_{tip}^2 R}$$

ρ : density, A : area of rotor disk,
V_{tip} : blade tip speed, μ : advance ratio (= V/V_{tip})

Note : Lift L is adjusted to the target thrust (=1080N), so C_{De} is in fact the objective function

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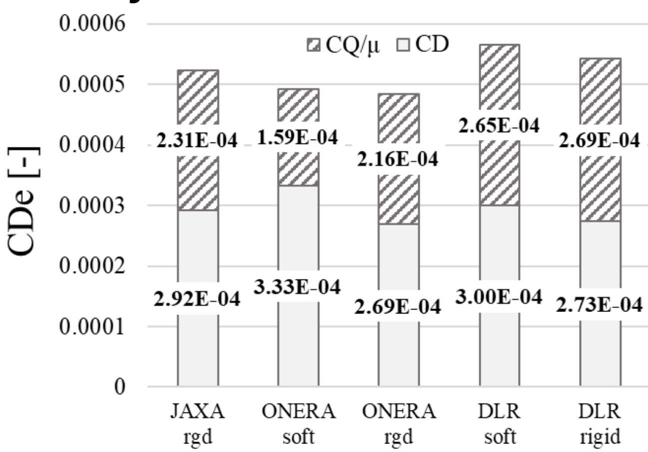
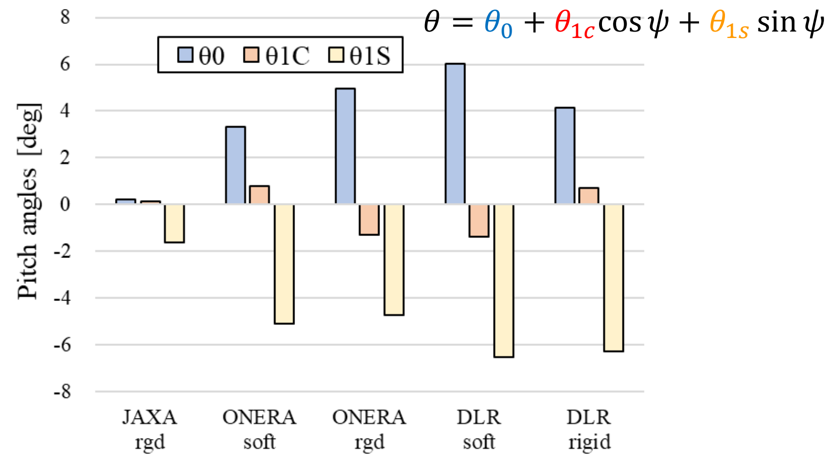
Baseline simulation

Low-fidelity method

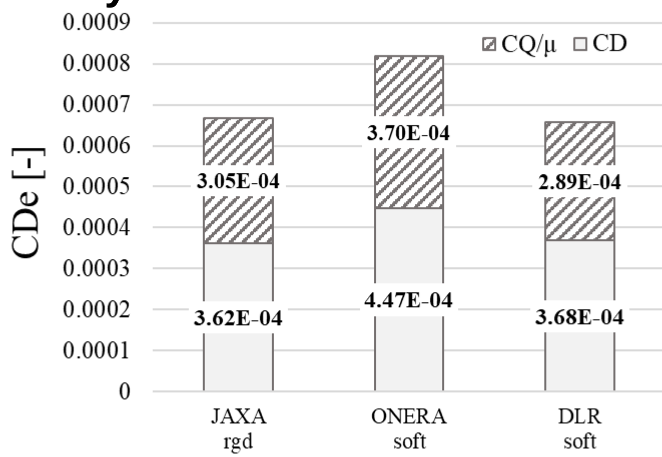


Effective drag

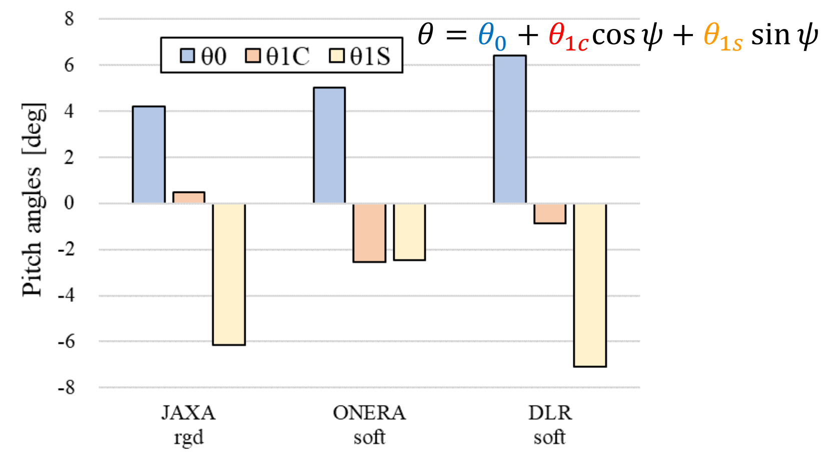


Pitch angle history (collective, lat-cyclic, longi-cyclic)

High-fidelity method



Effective drag



Pitch angle history (collective, lat-cyclic, longi-cyclic)

- ✓ Perform baseline blade analysis with Low/High-fidelity solver and compare results

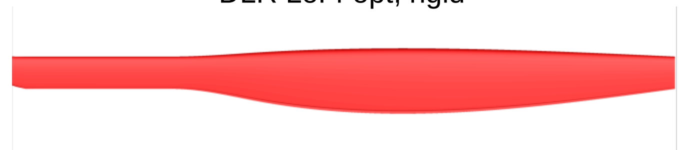
Obtained shapes

Planform

Baseline (HARTII)

DLR LoFi-opt, rigid

DLR LoFi-opt, elastic



DLR HiFi-opt, elastic

ONERA LoFi-opt, rigid

ONERA LoFi-opt, elastic

JAXA LoFi-opt, rigid

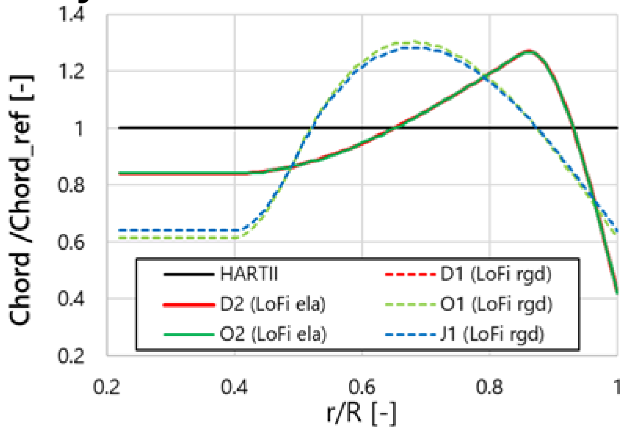
JAXA HiFi-opt, rigid

✓ Several variations :
- solver for performance evaluation (low-fi or hi-fi)
- structural analysis (rigid or elastic)

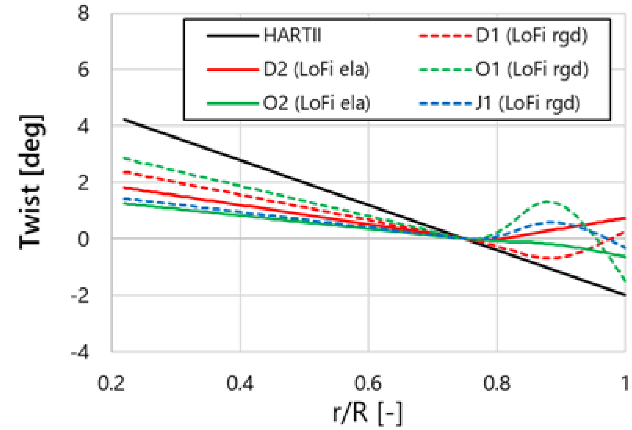
✓ smaller chord lengths at tip and root, larger chord at midsection

Obtained shapes

Low-fidelity method

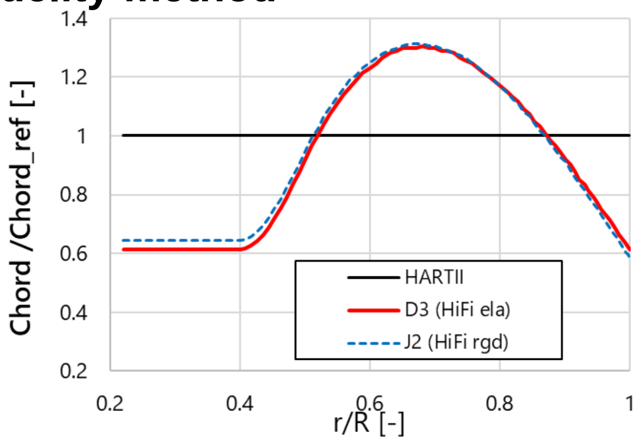


Chord distribution

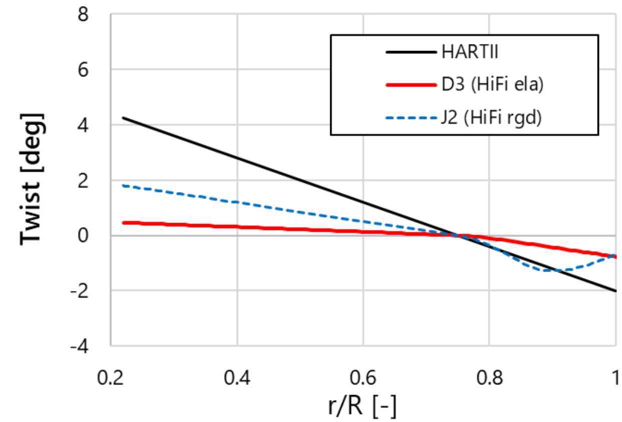


twist distribution

High-fidelity method



Chord distribution

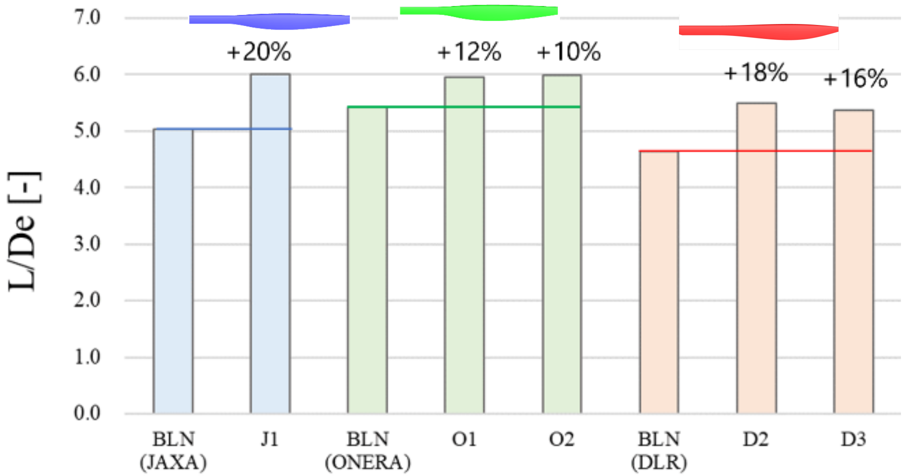


twist distribution

✓ smaller nose-down twist than Baseline

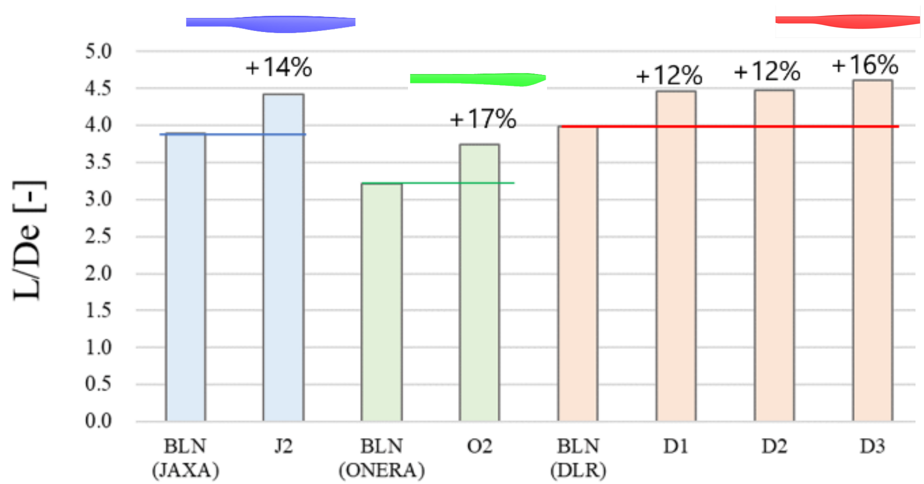
Performance of optimized blades

(a) Low-fidelity method



Effective lift to drag ratio L/De
(By Low-fidelity method)

(b) High-fidelity method



Effective lift to drag ratio L/De
(By Higi-fidelity method)

✓ confirmed 10~20% improvement in forward flight performance (L/De) from HARTII blades through optimization

J1 (JAXA, LoFi, rigid)
O1 (ONERA, LoFi, rigid)
D1 (DLR, LoFi, rigid)
D3 (DLR, HiFi, elastic)

J2 (JAXA, HiFi, rigid)
O2 (ONERA, LoFI, elastic)
D2 (DLR, LoFi, elastic)

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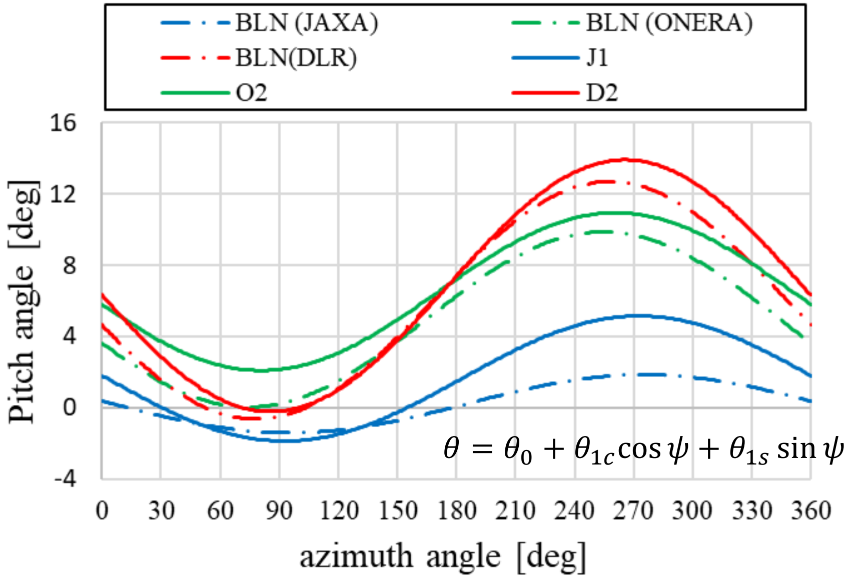
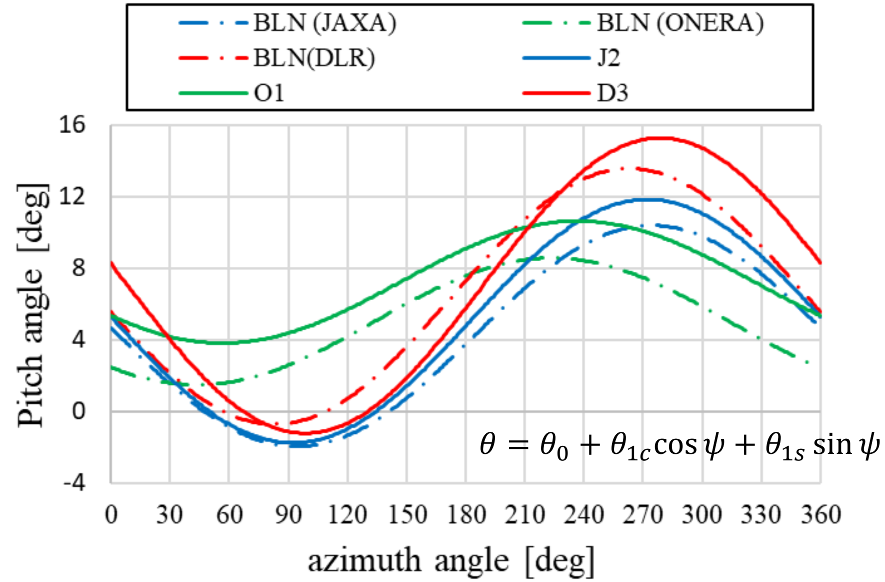
Pitch controls

(a) Low-fidelity method



Pitch angle history (Low-fidelity method)

(b) High-fidelity method



Pitch angle history (High-fidelity method)

- ✓ Pitch control tends to be larger to compensate for the smaller nose-down twist.

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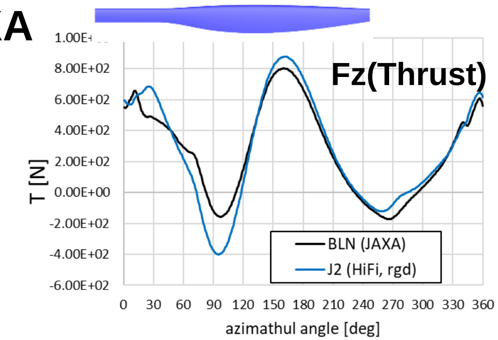
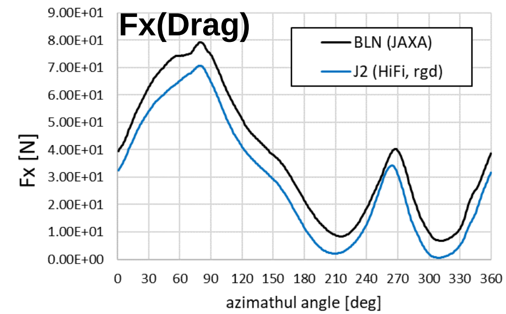
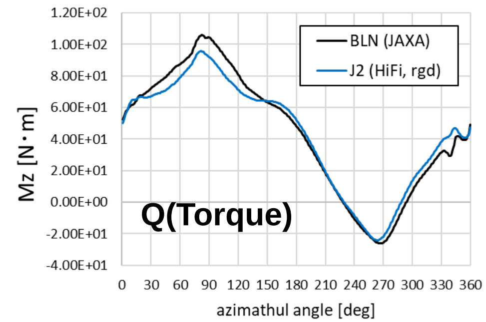
Azimuthal Force history

Ψ = 0~180° (advancing-side)
Ψ = 180~360° (retreating-side)

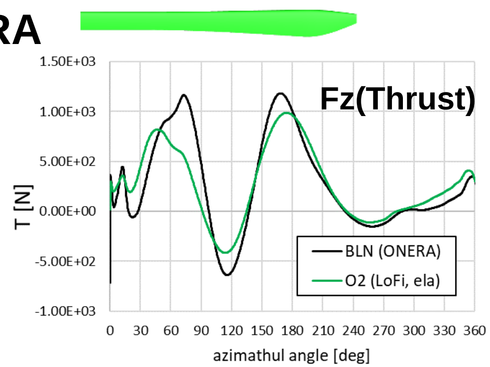
JAXA

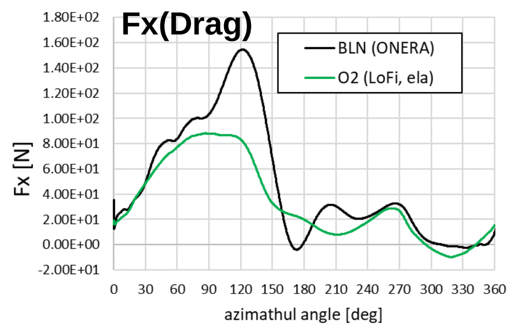


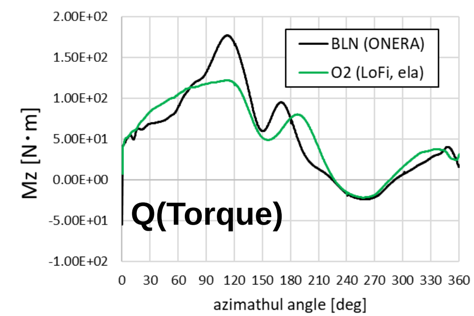




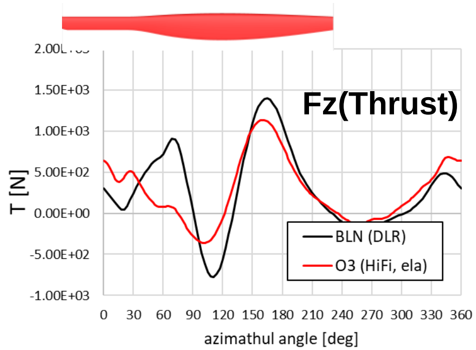
ONERA

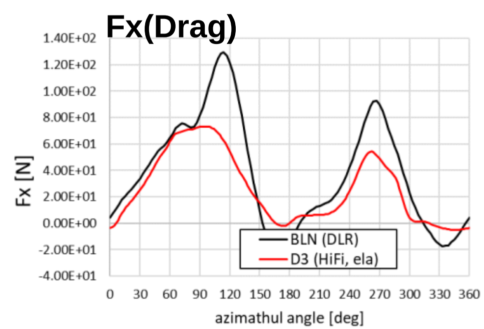


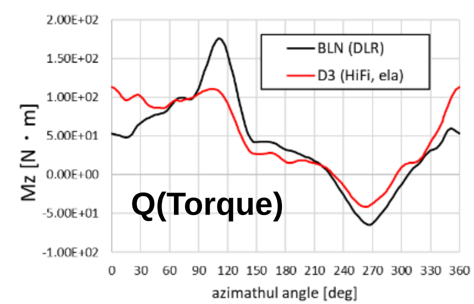




DLR

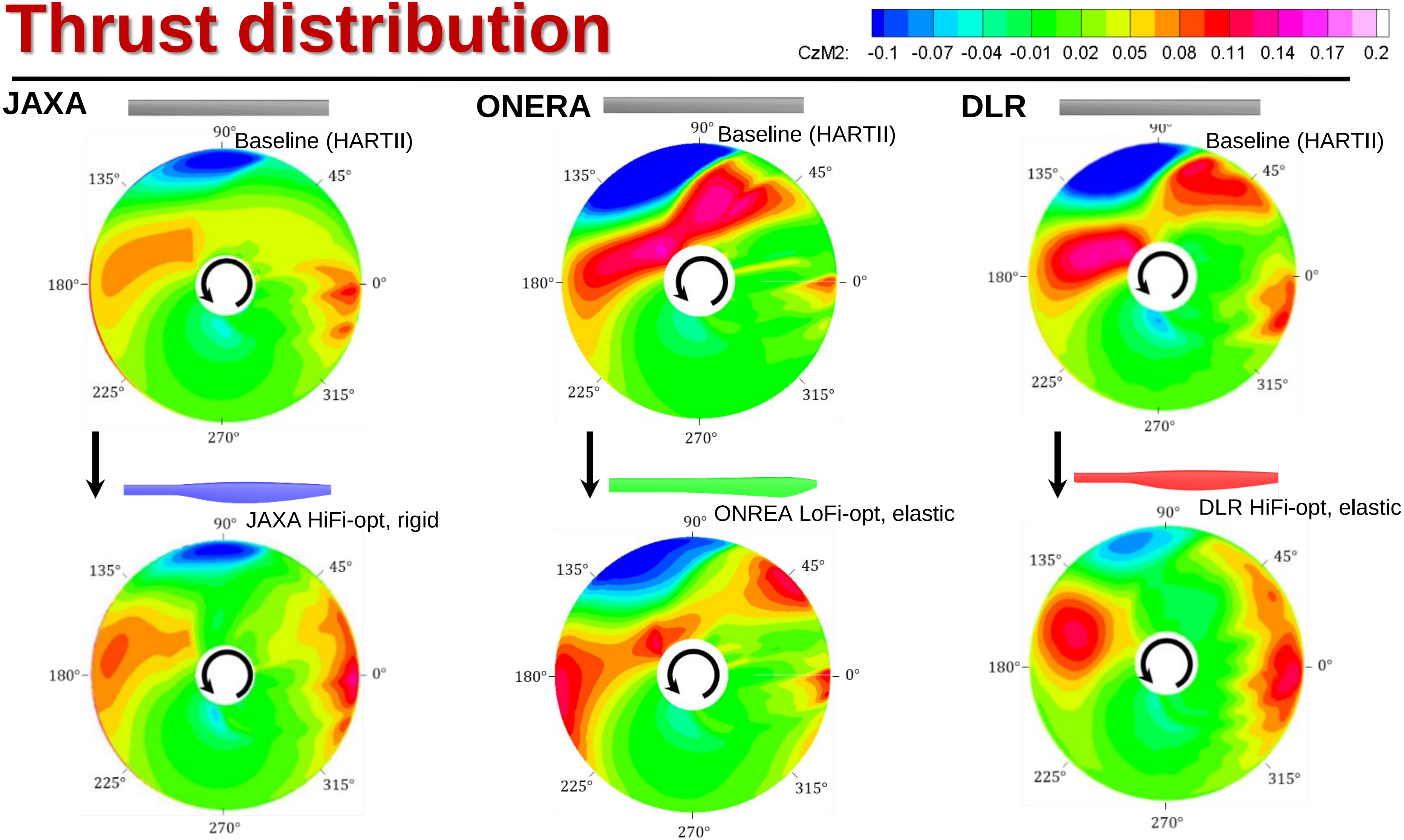






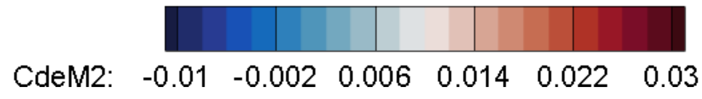
- Noticeable improvement in Drag and Torque on the advancing side (around ψ=90°)

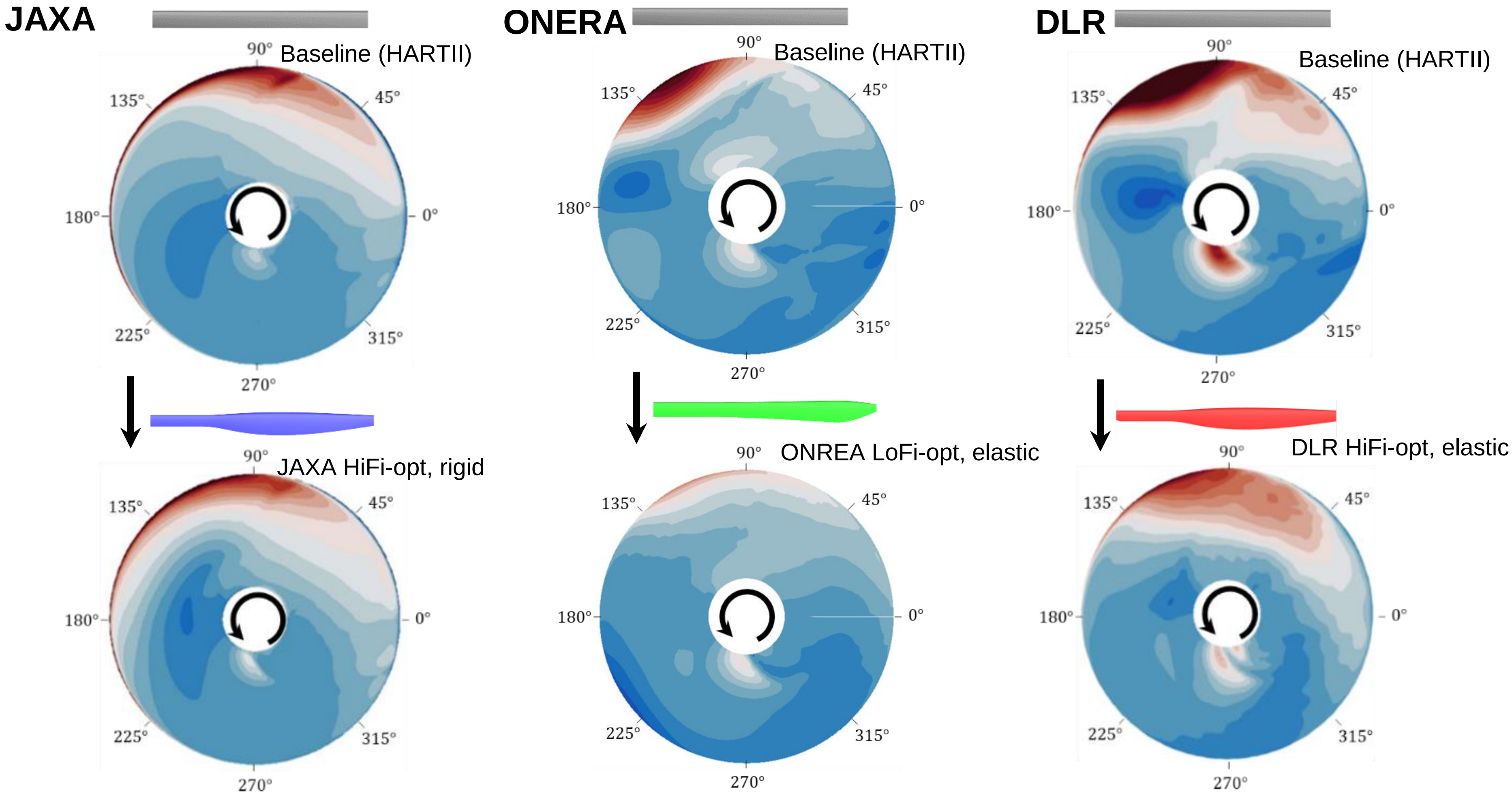
Thrust distribution



- ✓ Visualization of the thrust coefficient on the rotor disk (cal. By HiFi methods)
- ✓ Optimization changes the distribution to generate thrust in front and aft of the rotor
  ⇒ Advantageous in balancing rolling moments

Effective drag distribution





✓ HARTII's effective drag is concentrated at the blade tip on the advancing-side
⇒ Optimal blades reduce effective drag mainly in this area

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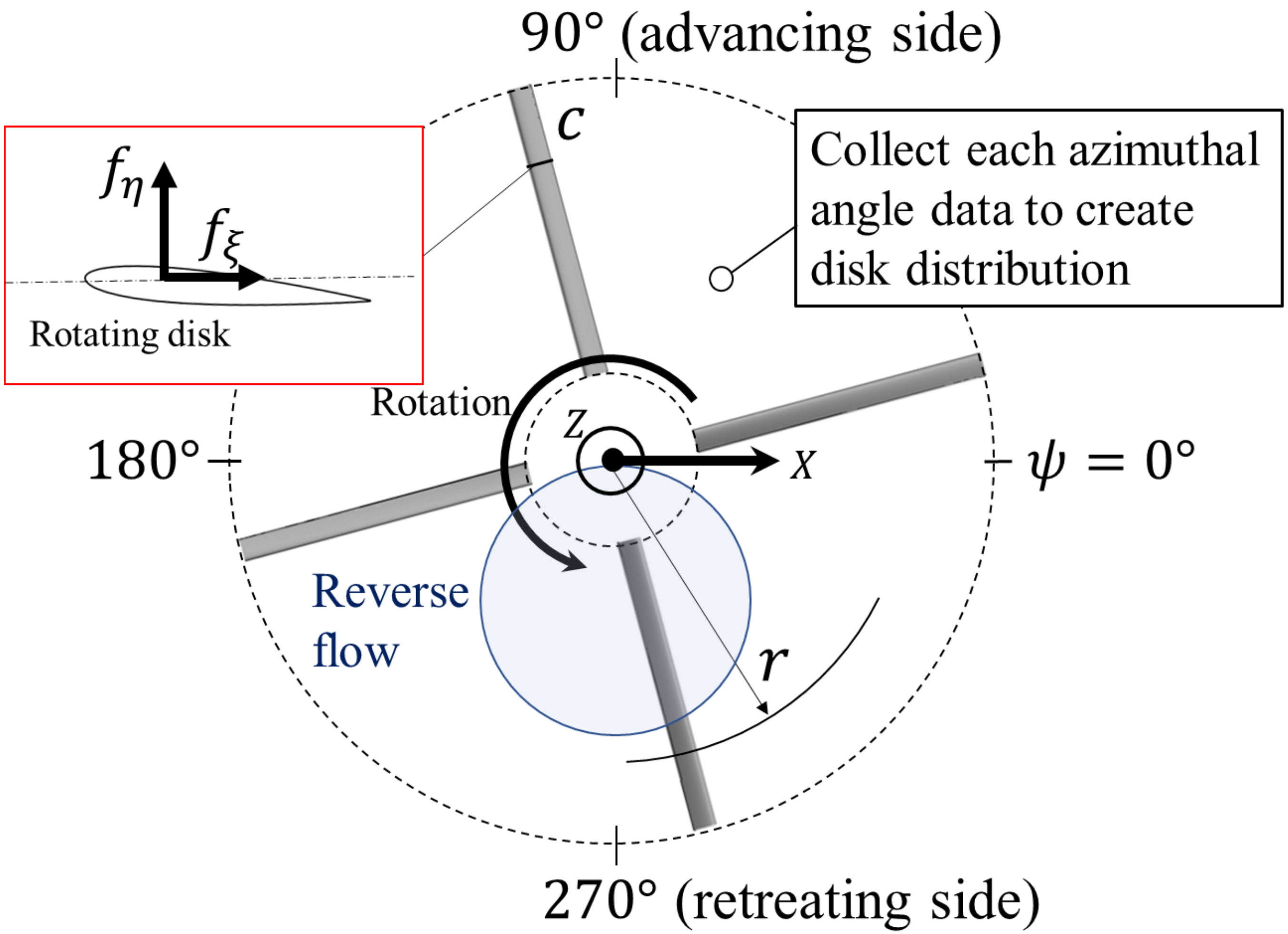
Concluding remarks

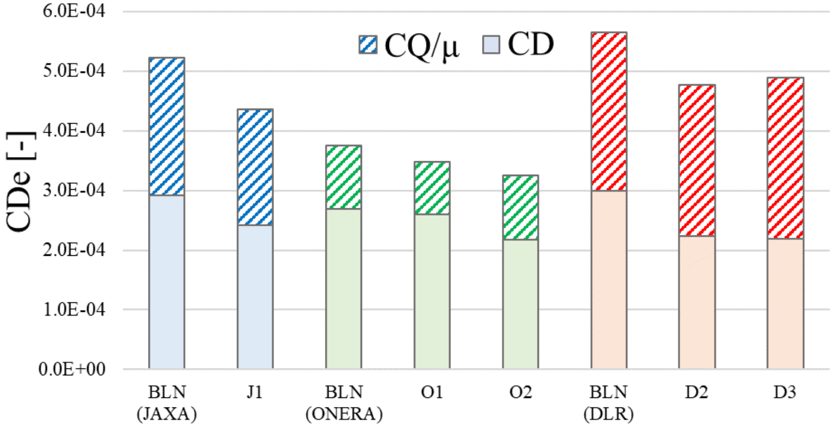
- JAXA, ONERA, and DLR collaborated on optimization to improve forward flight performance under high advance ratio conditions
- The optimization of the three institutions showed a common trend.
  Twist : smaller nose-down twist than Baseline
  Chord : smaller chord lengths at tip and root, larger chord at midsection
- The effective drag during forward flight is mostly carried by the blade-tip on the advancing side where the dynamic pressure acting on the blade is greatest, and it is important to reduce drag at this point.
- Conversely, reducing the retreating-side resistance is unlikely to reduce the running resistance because it works in the direction of increasing the rotor torque.

Thank you for your kind attention!

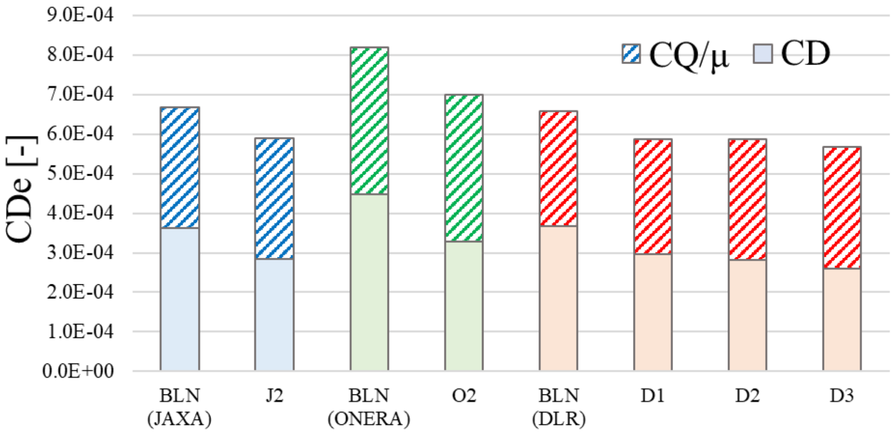
Disk distribution



Performance of optimized blades



Effective drag
(By Low-fidelity method)



Effective drag
(By Higi-fidelity method)