Boeing Higher Education Project 2023

Multi-objective design optimization of the multi-dispersed electric propulsion fan with regenerative air braking in a small passenger aircraft

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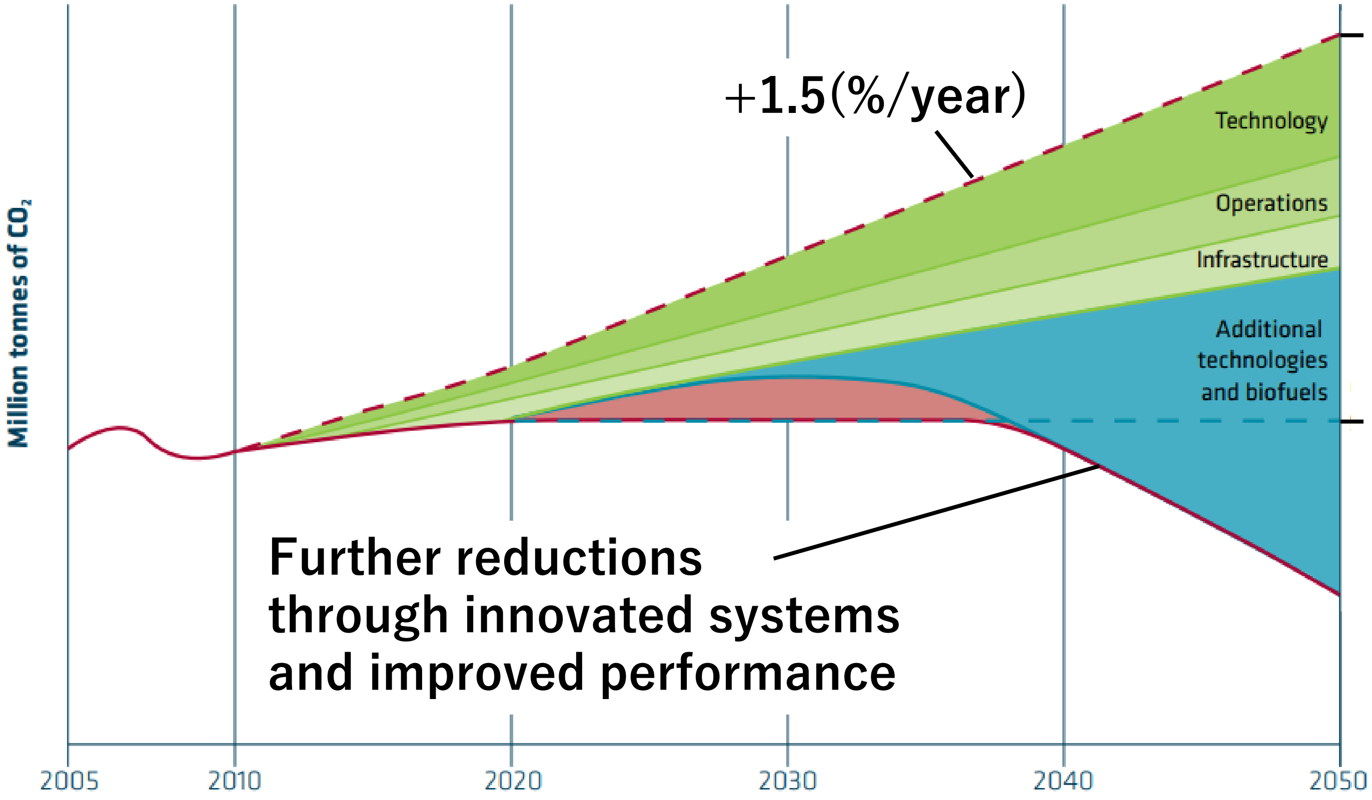
Background—Carbon neutrality by 2050



Scenarios for reducing CO2 emissions from **aircraft**[1]

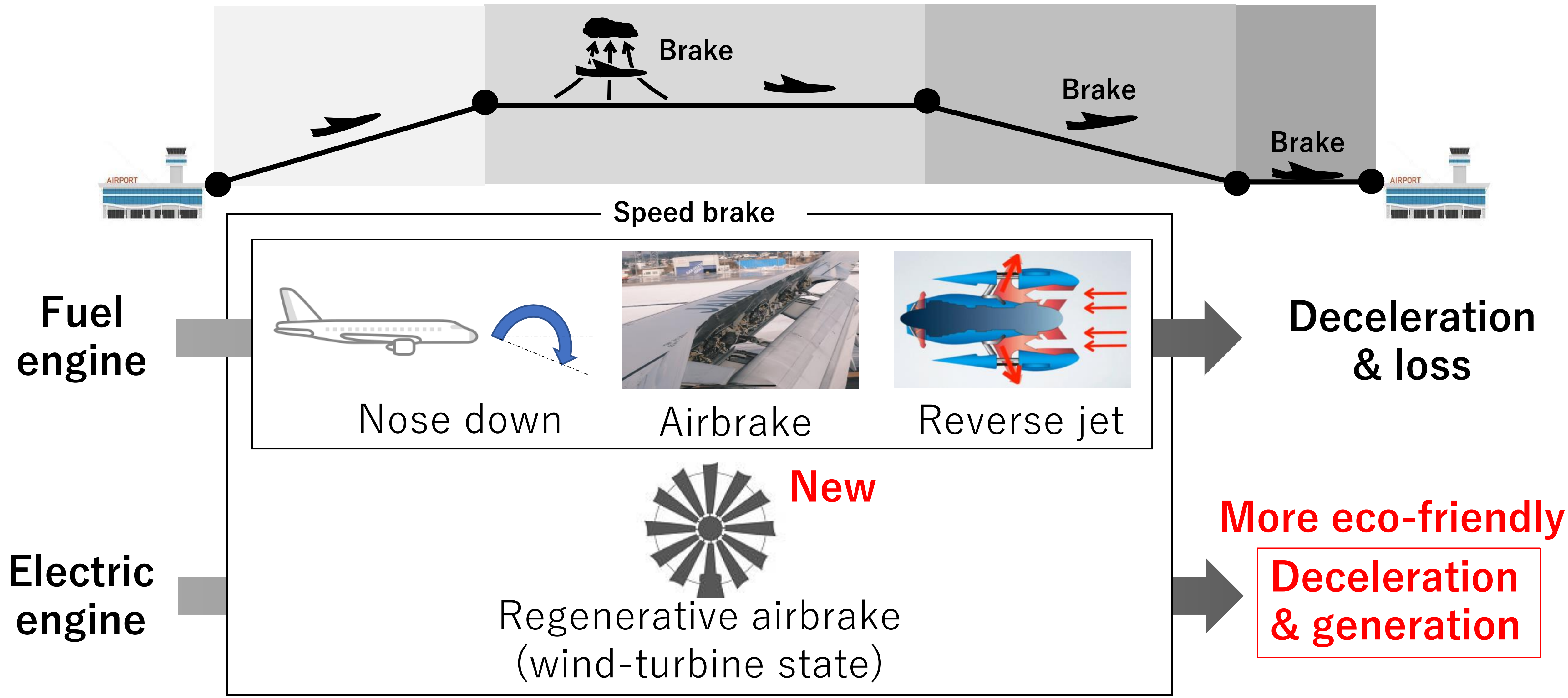
No action —— **Fuel engine**

Carbon-neutral

-50% by 2050 —— **Electric engine (Emission free flight)**

[1]WORKING PAPER DEVELOPED FOR THE 38th ICAO ASSEMBLY SeptOct 2013, “Reducing Emissions from Aviation through Carbon-Neutral Growth from 2020

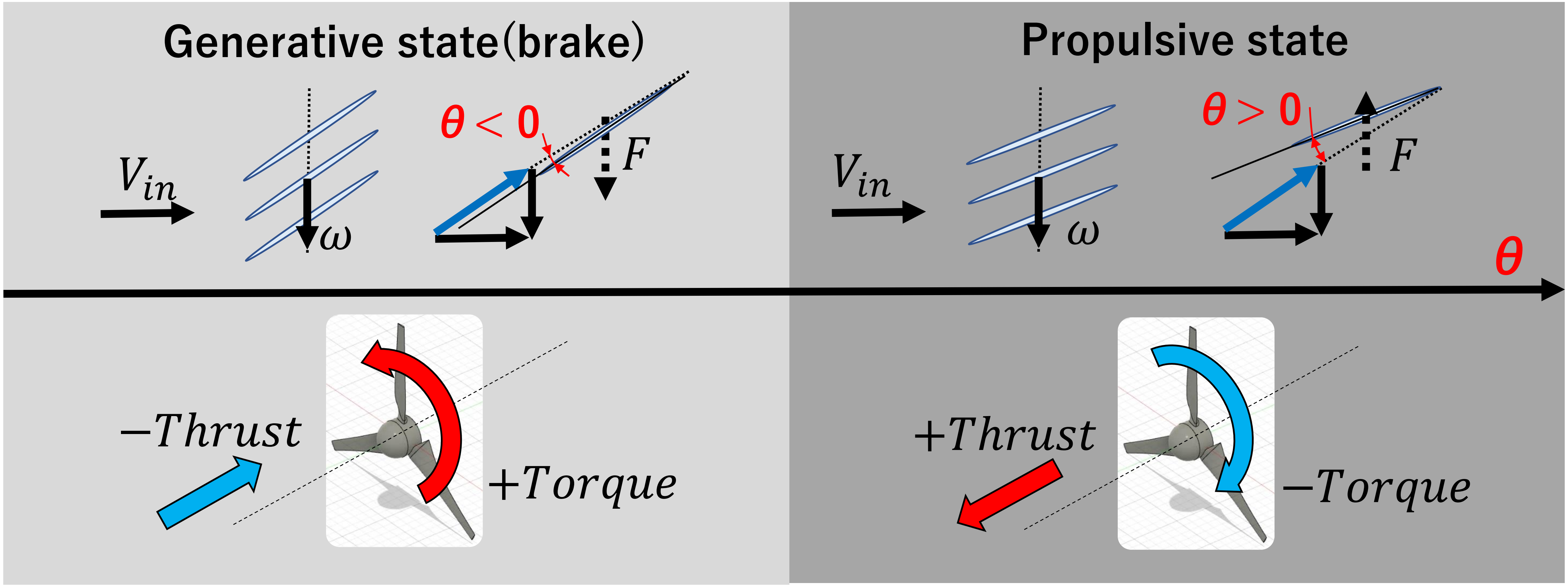
Background—Regenerative airbrake



[2] Akira Nishizawa, et al. Flight demonstration of Electric Aircraft Technology for Harmonized Ecological Revolution (FEATHER)65.7 ,2018

Background—Regenerative airbrake system for small aircraft (JAXA, 2015)

Adjusts **angle of attack**(θ) to switch between two states

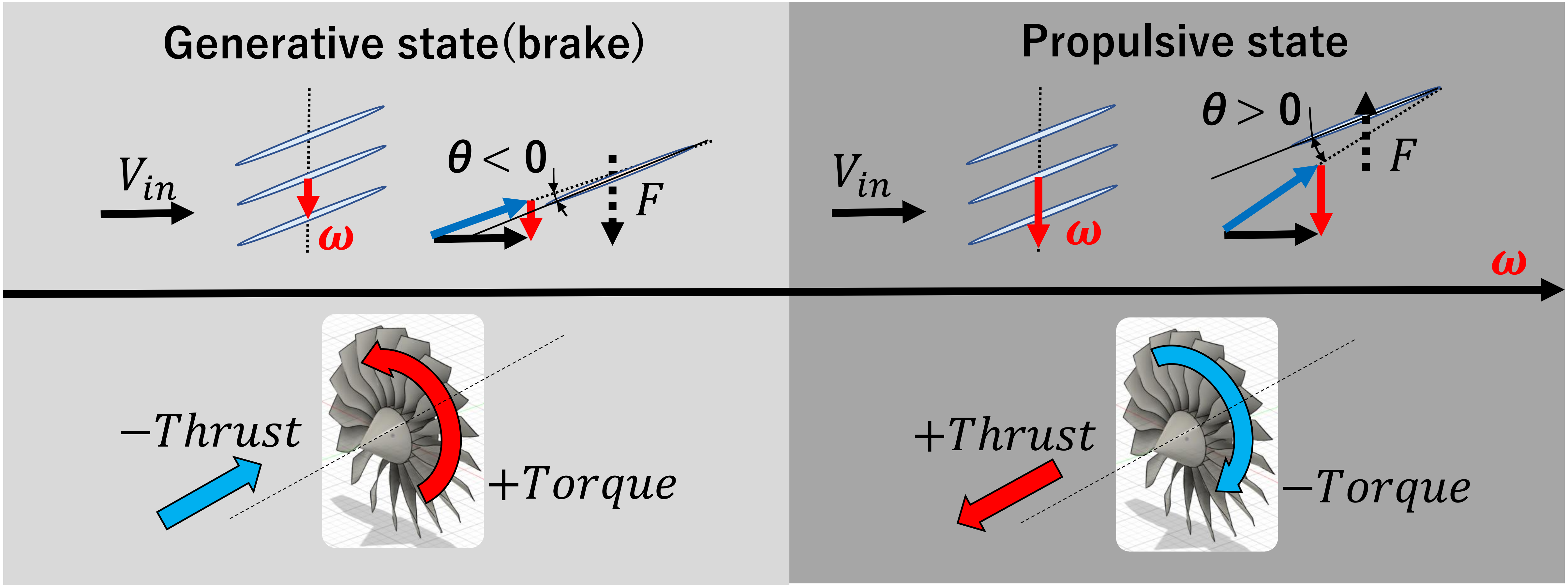


However, regenerative airbrakes have not been applied to fans with an invariable angle of attack used in many passenger aircrafts

[2] Akira Nishizawa, et al. Flight demonstration of Electric Aircraft Technology for Harmonized Ecological Revolution (FEATHER)65.7, 2018

Background―Regenerative airbrake system for passenger aircraft

Adjusts **rotation speed**(ω) to switch between two states



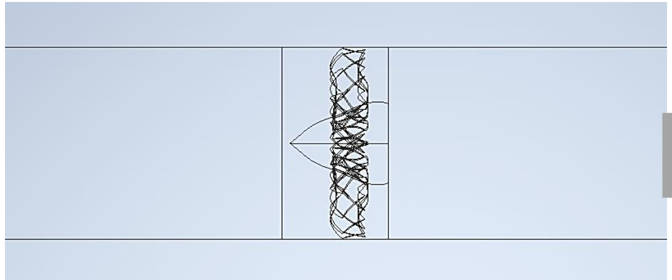
Ideally, a fan with high performance in both of these areas is required

Purpose

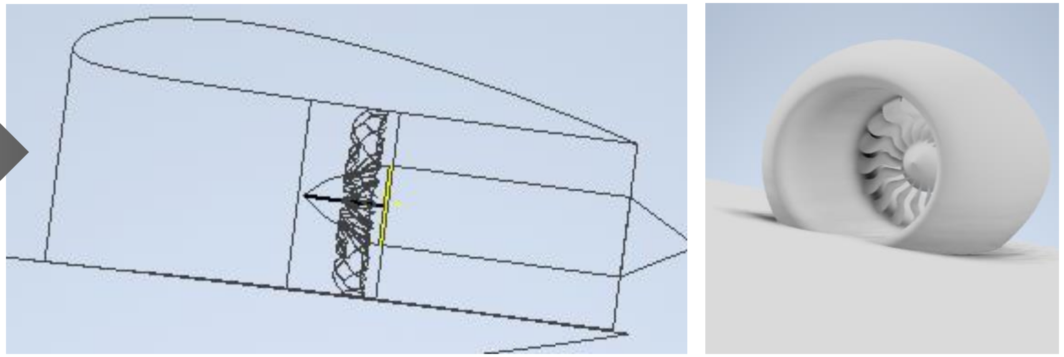
- Find the balanced design of an aircraft fan's efficiency in both states (propulsive and generative)

- Investigate the aerodynamic characteristics of a propulsion fan with regenerative air brake system

Problem 1



Problem 2

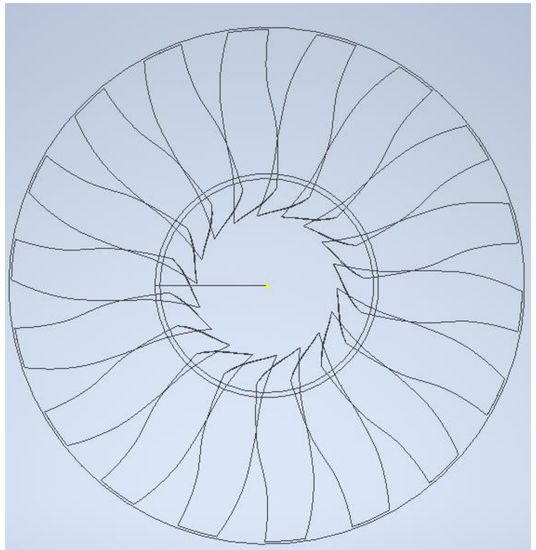


Circular flow field
(AJKFED 2023)

BLI flow field
(APS DFD 2023)

Problem settings―Target geometry & Design variables

Target geometry

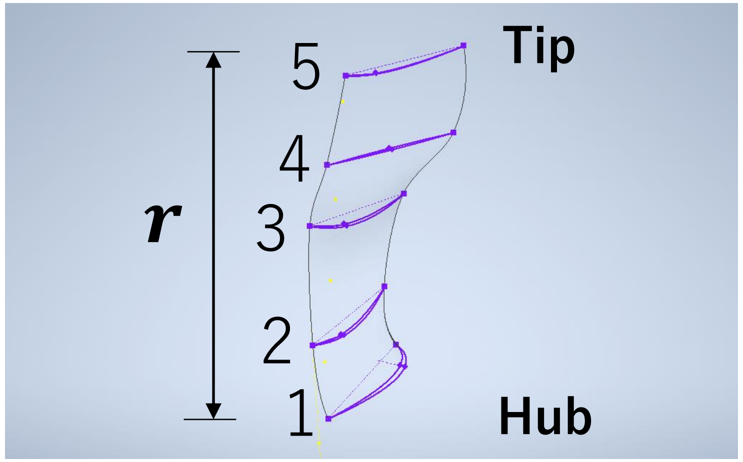


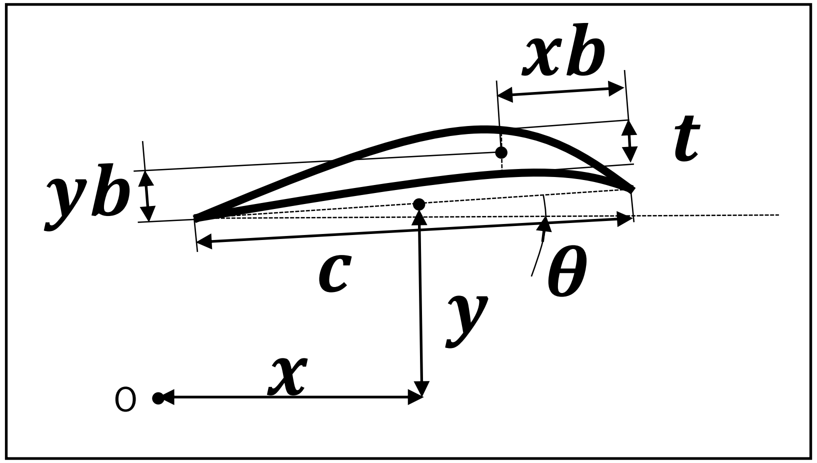
Propulsion fan

Blade number	18
Hub-model	LEAP 1-A [3]
Size	25% of LEAP 1-A

Design variables

Blade (33 variables**: $x, y, c, \theta, xb, yb, t$)** [4]





5 cross-sections

A cross-section: **7** variables

Tip speed ratio (2 variables**: rot_g, rot_p)** [3][5]

$$rot = \frac{r\omega}{V_{in}} \quad (\omega\ changes)$$

rot_g: 0~1

rot_p: 1~2

[3]Airbus. AIRCRAFT CHARACTERISTICS AIRPORT AND MAINTENANCE PLANNING, 2005
[4] Wu, Long, et al. "Low-Noise Blade Design Optimization for a Transonic Fan Using Adjoint-Based Approach." AIAA Journal 60.4, 2022
[5] Masashi Nishikata, et al. Easy-to-understand wind power generation, 2013

Problem settings—Optimization objectives & aerodynamics characteristics

The physical quantities $(T_0\,, P_0)$ are obtained at ***In*** and ***Out***

T_0: *Total temperature* [K] P_0: *Total pressure* [Pa]

<Objectives>

1 $\boldsymbol{max}\ \eta_p$:Isentropic efficiency [6]

$$\frac{\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}}-1}{\left|\frac{T_{02}}{T_{01}}-1\right|}$$

⇒ **Lower compression loss**

2 $\boldsymbol{max}\ \eta_g$:Total pressure efficiency [7]

⇒ **Higher generation during brake**

Q: *Flow rate* $[\mathrm{m^3/s}]$ τ: *Torque* [Nm]

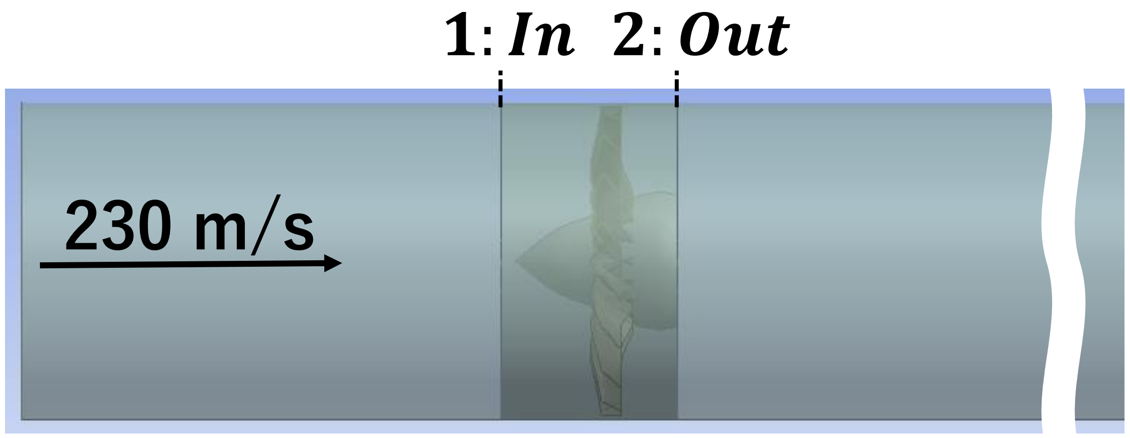
$$\frac{\tau_g \times \omega_g}{|p_{01} - p_{02}| \times Q}$$

<Constraint>

1 π_p >1.2 :Total pressure ratio [6][8]

$$\frac{P_{02}}{P_{01}}$$

⇒ **Satisfy the required thrust**



CFD conditions

Flight altitude	40000 feet
Flight velocity	230 m/s (Mach 0.78)
CFD Solver	ANSYS CFX®
Turbulence equation	RANS
Flow condition	Steady
Rotation speed	ω_p, ω_g

[6] H.I.H Saravanamuttoo, et al., Gas Turbine Theory, 2017
[7] Shinichi Oda, et al. Research of electric power regeneration using automotive cooling fan, 2015
[8] Taguchi Hideyuki, et al. Performance and Weight Estimation of Next Generation Jet Engines, 2021

Design optimization method—Bayesian optimization

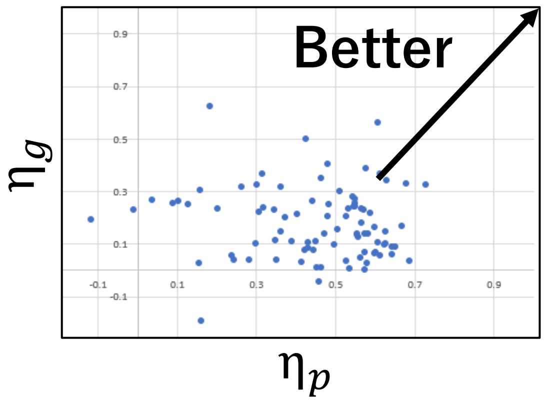
- Global optimization in high-dimensional space (35 design variables)
- High cost CFD analysis (1 case: 8 hours)

⇒ Bayesian optimization [9]

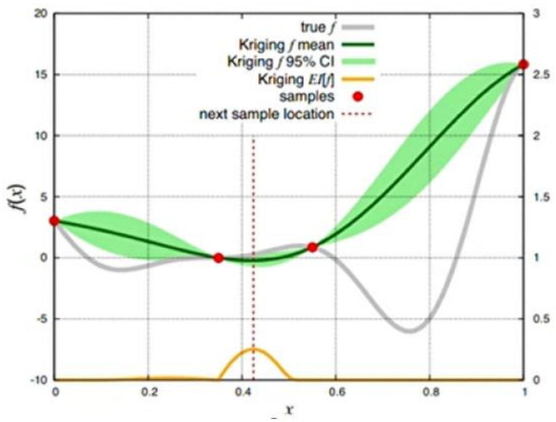
(A stochastic global optimization method using approximate functions)

[9] Carl Edward Rasmussen, et al. Gaussian Processes for Machine Learning,2005.

Design optimization method—Bayesian optimization



Create the initial samplings & evaluate using CFD



Construct approximate functions $\hat{f}$ with uncertainty $\hat{s}$

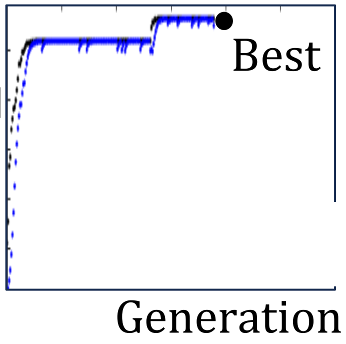
Converged

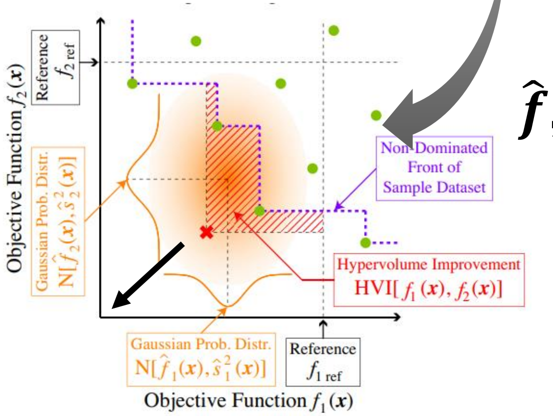
End

Not converged

$\hat{f}$, $\hat{s}$

CFD & add samples

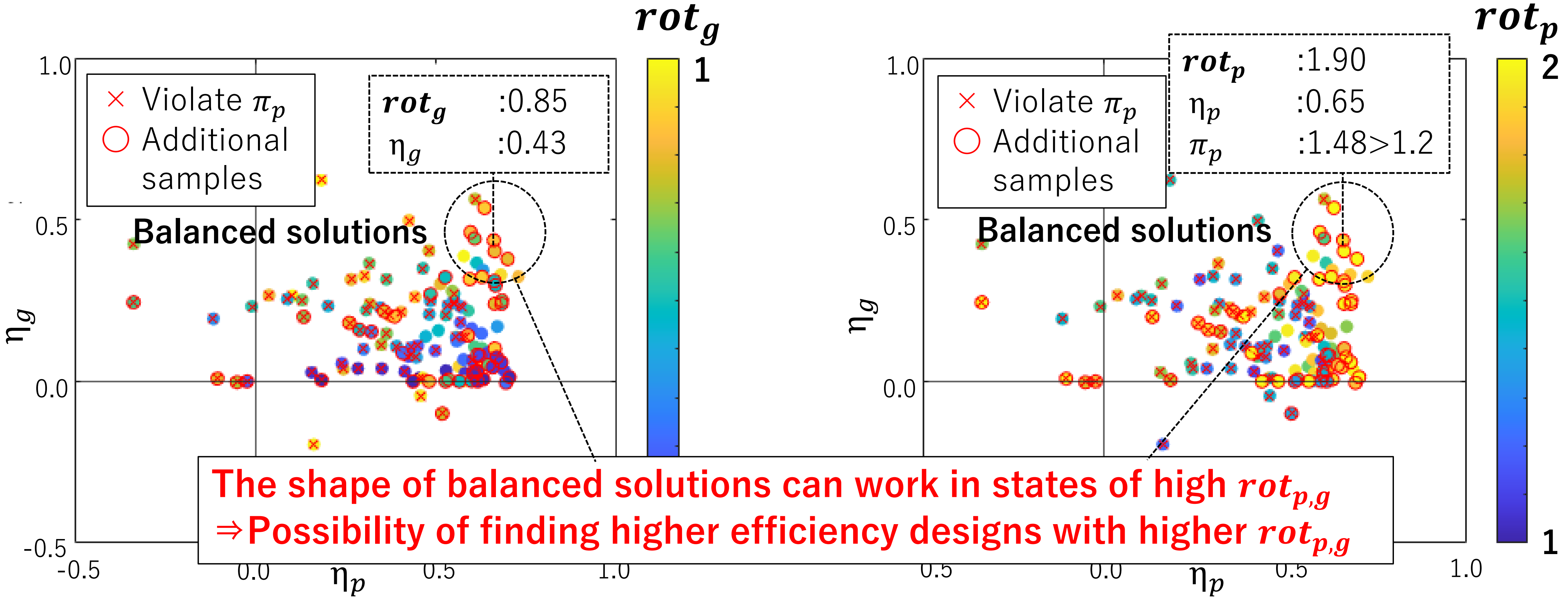




Locate the best samples based on improvement of $\hat{f}$ and $\hat{s}$

[9] Carl Edward Rasmussen, et al. Gaussian Processes for Machine Learning,2005.

Number of additional samples: 5 samples × 14 updates



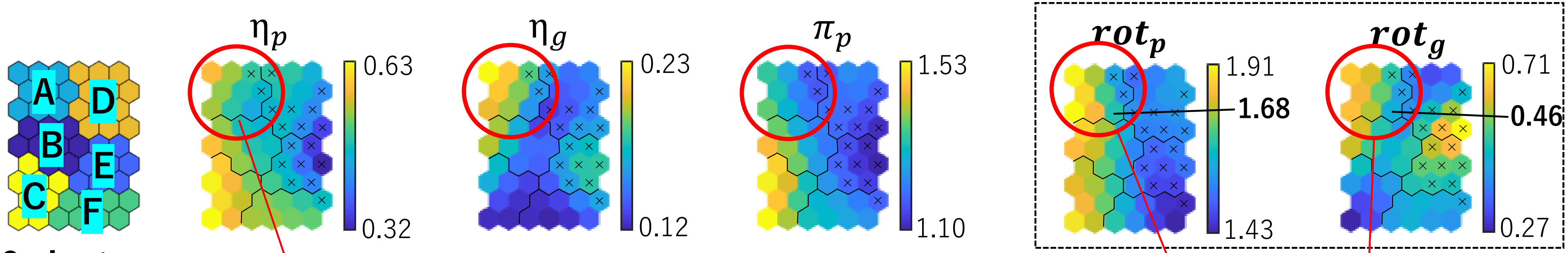
The shape of balanced solutions can work in states of high $rot_{p,g}$
⇒Possibility of finding higher efficiency designs with higher $rot_{p,g}$

[9] Carl Edward Rasmussen, et al. Gaussian Processes for Machine Learning,2005.

Results—Problem 1: Visualization of design space (Objective functions)

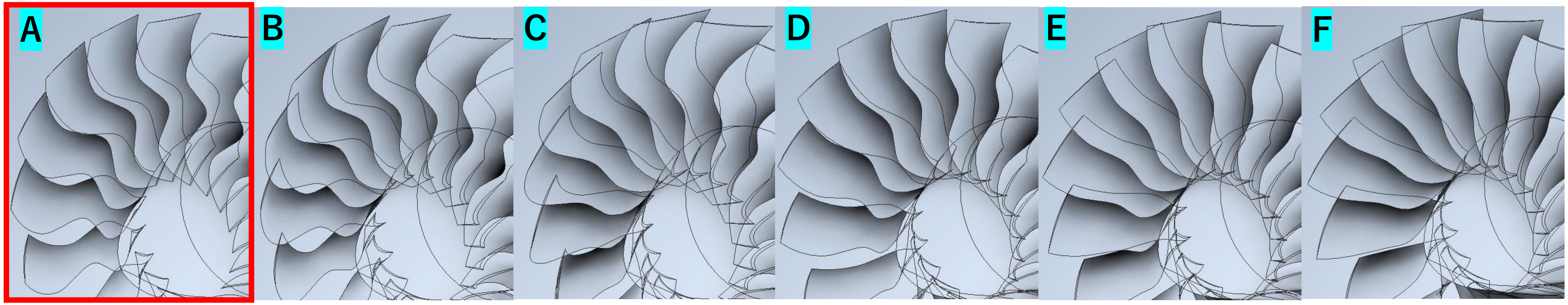
Self-organizing map ：
Visualize the relationship of each variable in the data by mapping multi-dimensional data onto two-dimensional planes

× Violate π_p



6 cluster

Balanced solution: Relatively high η_p, η_g, π_p>1.2 High rot area



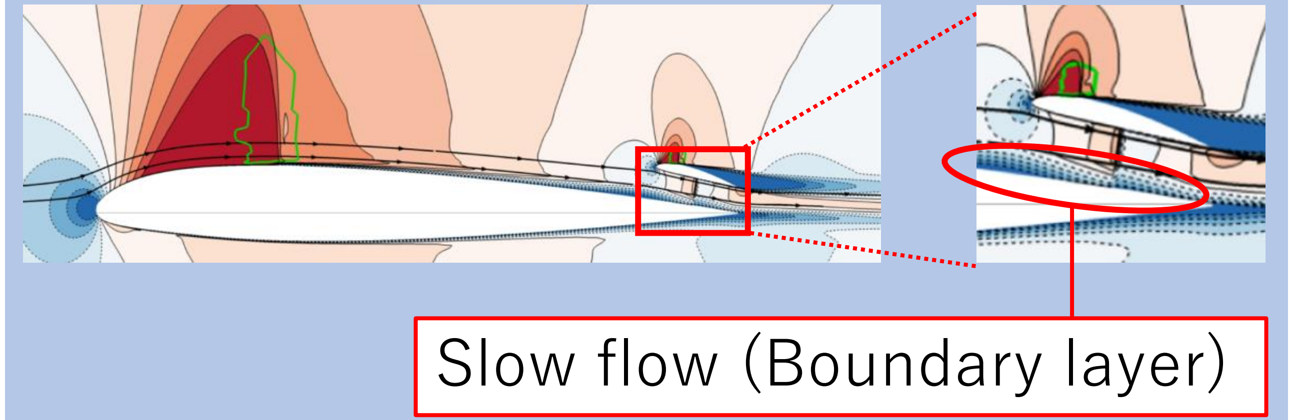
Problem 1 … **Possibility of finding higher efficiency designs with higher $rot_{p,g}$**

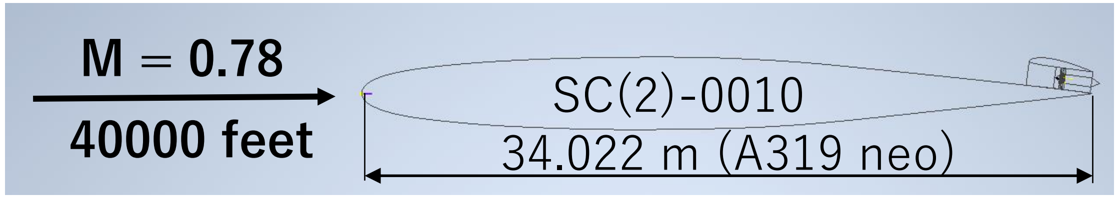
To realize much higher $rot_{p,g}$ to improve fan performance …

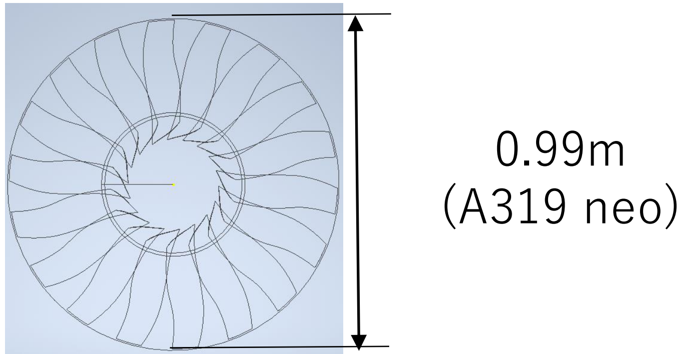
→ **Application of BLI to decrease inlet velocity (V_{in})**

$$rot = \frac{r\omega}{V_{in}}$$

Boundary layer ingestion (BLI)







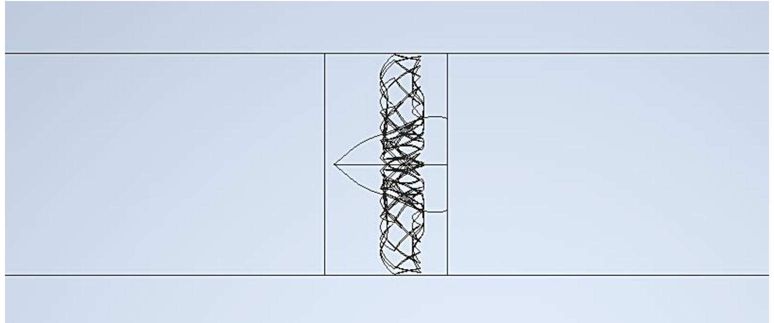
⇒Design optimization of a BLI propulsion fan with regenerative air brake

※Changes from Problem 1 rot_g: 0~1⇒ 0~1× rot_p

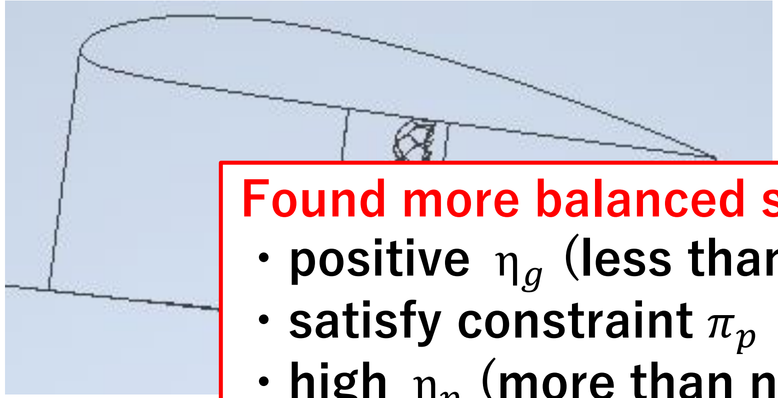
[5] Arntz, Aurélien, and Olivier Atinault. Exergy-based performance assessment of a blended wing–body with boundary-layer ingestion. 2015

Results—Problem 1&2: Optimization (100 samples + 5 adds × 14 updates)

η_p : Isentropic efficiency (Propulsion)
η_g : Total pressure efficiency (Generation)



Non-BLI (Problem 1)

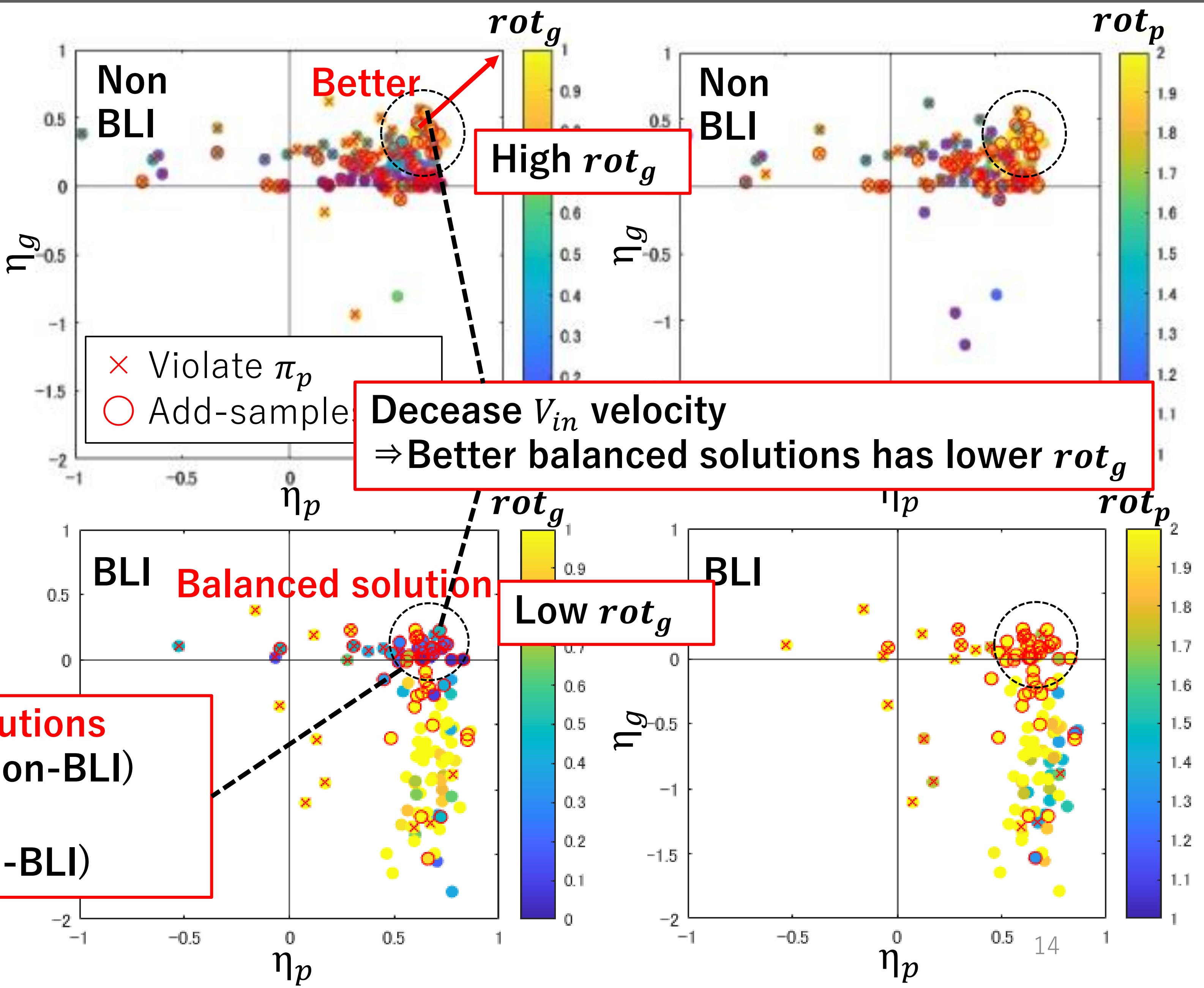


BLI (Problem 2)

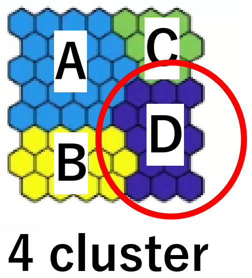
※ Decrease V_{in} velocity

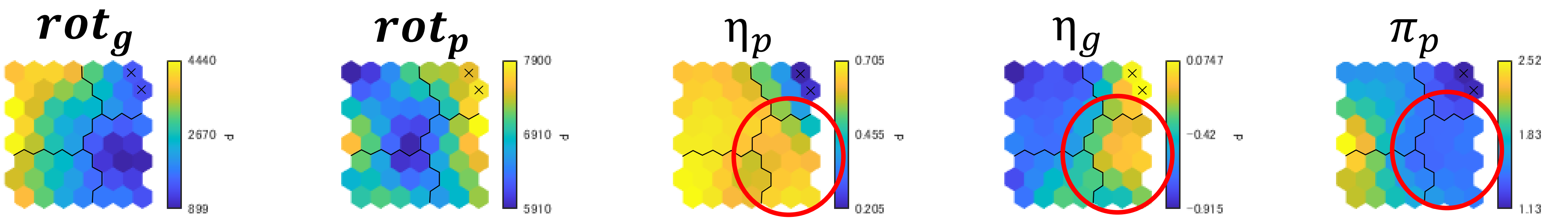
Found more balanced solutions

- positive η_g (less than non-BLI)
- satisfy constraint π_p
- high η_p (more than non-BLI)

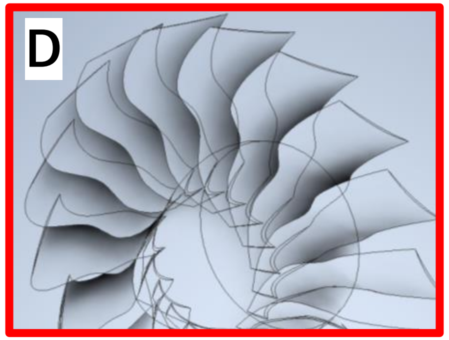


Result—Problem 2: Visualization of the design space

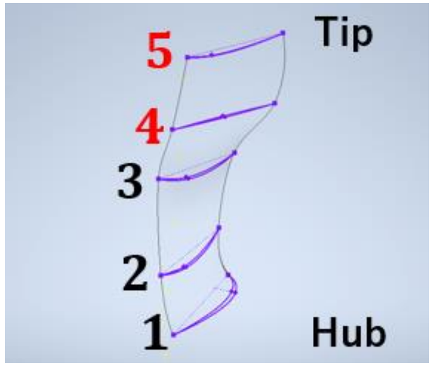


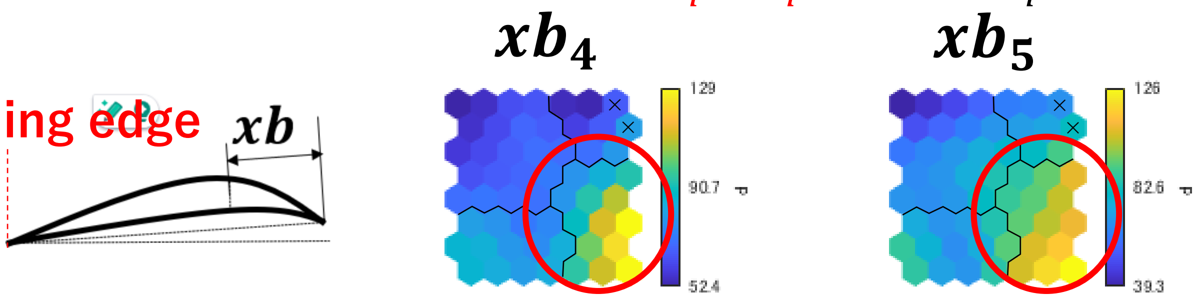


Balanced solution: relatively high η_p, η_q, satisfy $\pi_p > 1.2$

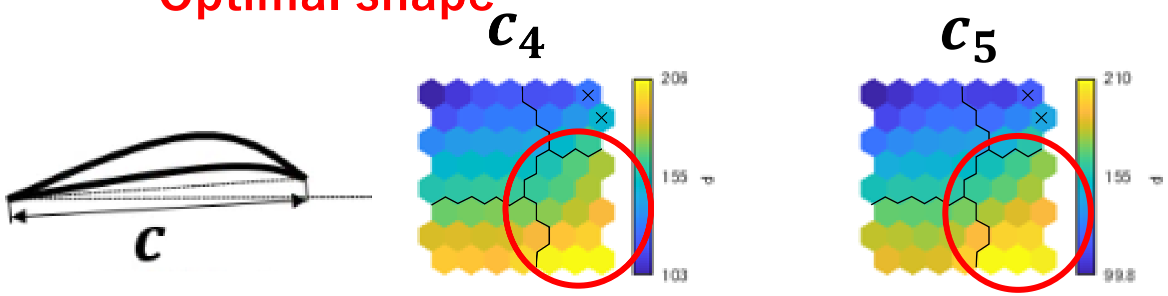


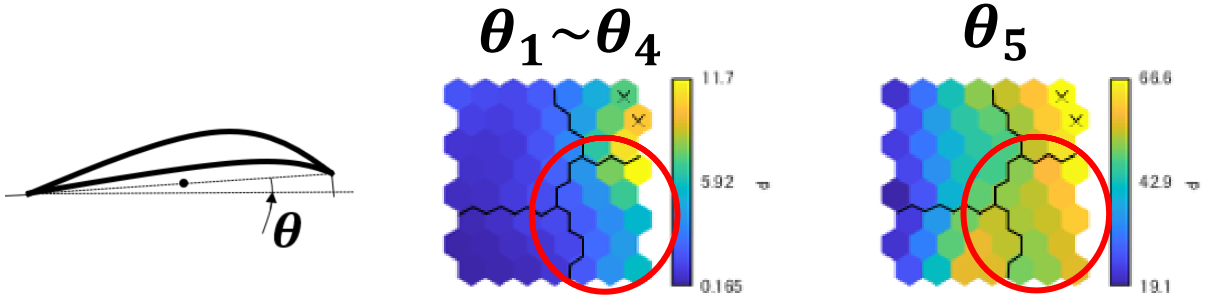
Optimal shape





⇒Max camber is at near trailing edge





⇒Larger chord length

⇒Tip angle of attack increases suddenly

The shape near the wing tips, where the BLI flow field appears, plays a major role in the optimal shape

Summary (Problem 1&2)

The design of a fan capable of generating electricity and propulsion has been implemented using the stochastic Bayesian optimization method,
successfully generating several shapes with balanced performance in both states

Problem 1 (Simplified setting):

1 Fans with regenerative air braking can be realized in regions with relatively high tip speed ratios during propulsion and power generation

2 Smaller chord length and more warped in the opposite direction of rotation

Problem 2 (Higher tip speed ratio):

1 Fans with regenerative air braking using BLI can be realized in regions with relatively high tip speed ratio during propulsion and generation but, it is limited to the tip speed ratio range where regeneration is possible

2 The important shape characteristic of a BLI propulsion fan appears near the wing tips of larger chord length, maximum camber is at near trailing edge, and angle of attack increases suddenly

Acknowledgment

Thank you very much for the Boeing company's financial support and listening to my presentation!!

Purchased items:

・Workstation
・RAM
・Tablet
・Mouse