

## 第12回「IEA Windセミナー」

# Task44: ウィンドファームの流れ場制御

### ■ Operating Agents

Paul Fleming (NREL), Jan-Willem van Wingerden (TU Delft)

### ■ Web Page

<https://iea-wind.org/task44/>



うちだ たかのり

内田 孝紀

応用力学研究所/再生可能流体エネルギー研究センター/  
洋上風力エネルギー高度利用分野/教授

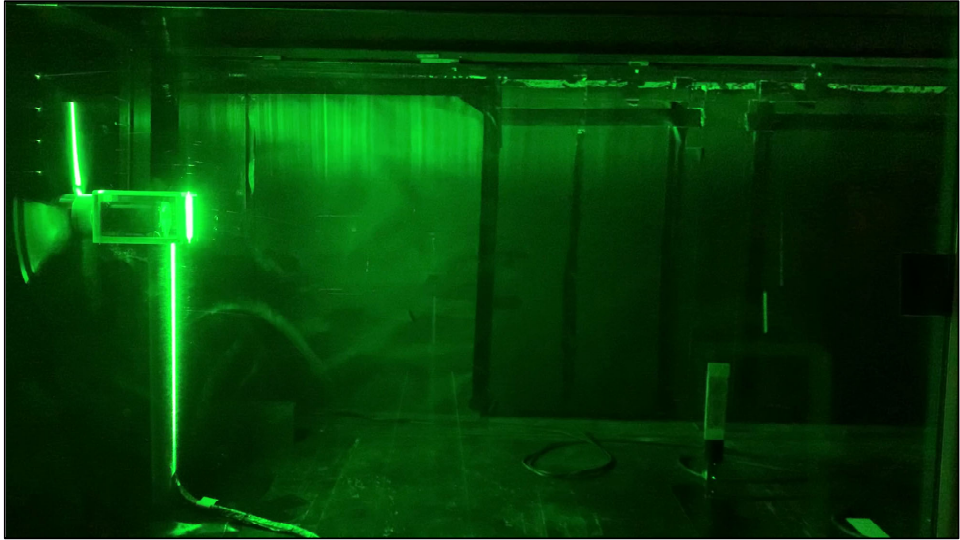
兼務：洋上風力研究教育センター/  
マルチスケール洋上風況研究部門/部門長



九州大学  
KYUSHU UNIVERSITY

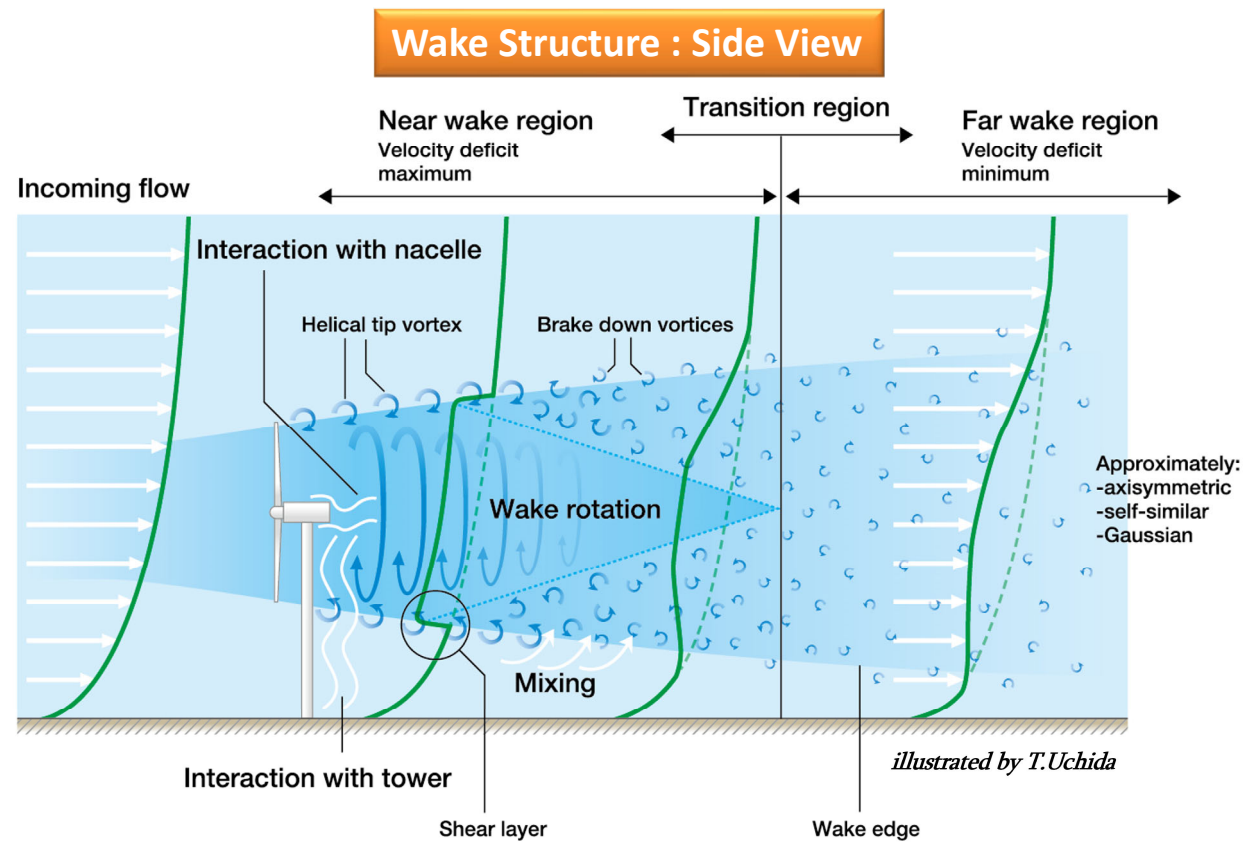


# IEA Wind TCP Task44

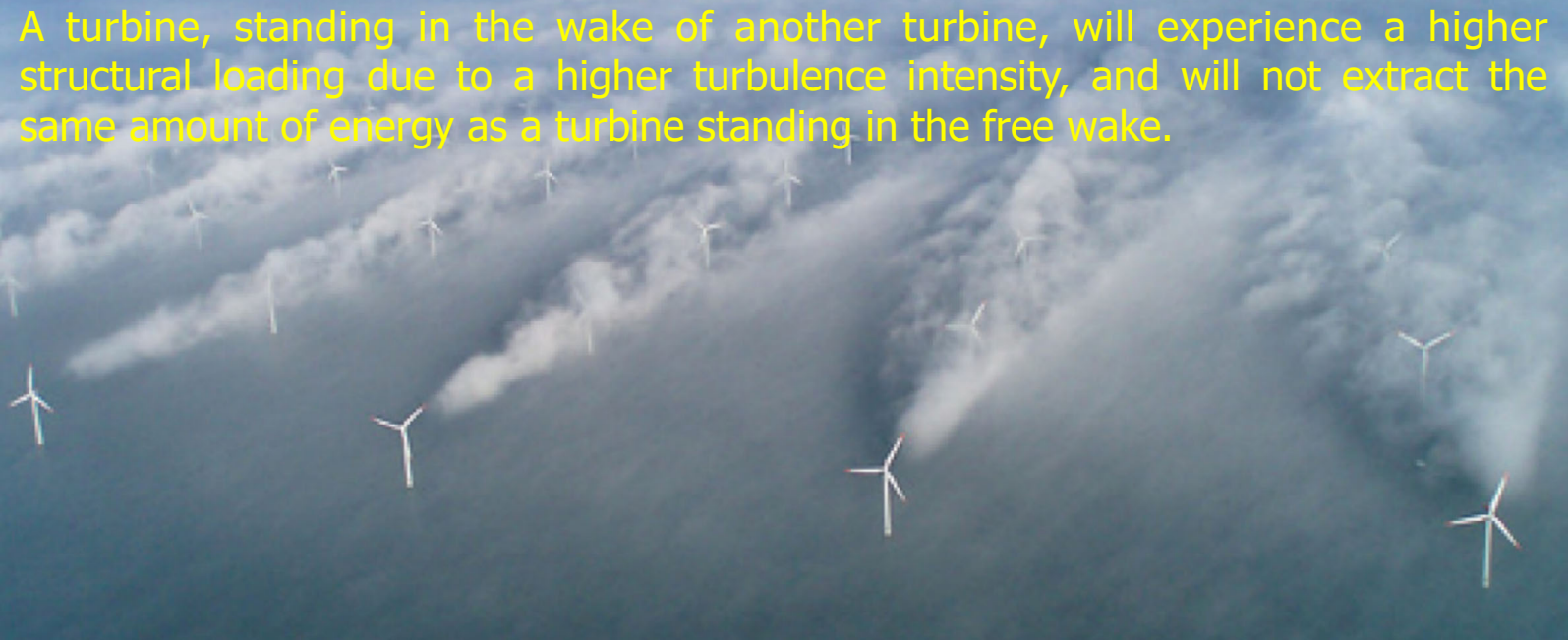
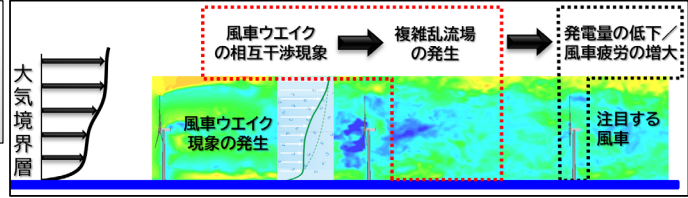


九州大学応用力学研究所  
温度成層風洞にて撮影  
2020年11月12日

## What is the wind turbine wake phenomenon ?



# IEA Wind TCP Task44



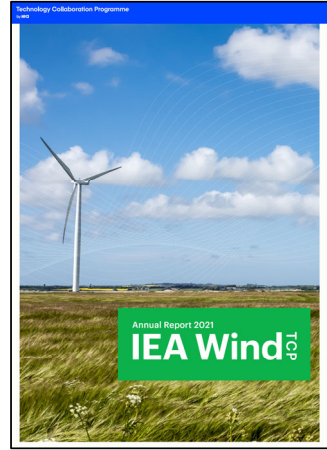
A turbine, standing in the wake of another turbine, will experience a higher structural loading due to a higher turbulence intensity, and will not extract the same amount of energy as a turbine standing in the free wake.

- Photograph taken by Christian Steinus in 2008, photo taken on the special atmospheric conditions.
- And what we nicely can see in this photograph is that there is interaction between turbines, so wake interaction.



Wind farm control is an active and growing field of research in which the control actions of individual turbines in a wind power plant are coordinated to minimise wake interactions.

ウィンドファーム制御は、風力発電所内の個々の風車の制御動作を調整して、風車ウエイクの相互作用を最小限に抑える、活発で成長している研究分野である。



# IEA Wind TCP Task44



- 国際エネルギー機関(IEA)は、風力技術協力プログラム(略称:IEA Wind TCP)を主催している。
- IEA Wind国内委員会(締約機関:NEDO)からの推薦・審議を経て、IEA Windの国際共同研究活動(Task 44)に参画している(2021年12月15日～)。

## Task 44 (Wind Farm Flow Control) のスコープ

- 風力発電所の制御分野における**国際共同研究**
- 風力発電所の制御アルゴリズムと性能向上への貢献が焦点

(研究の目的)

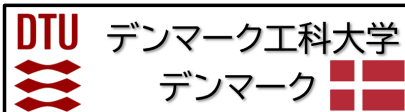
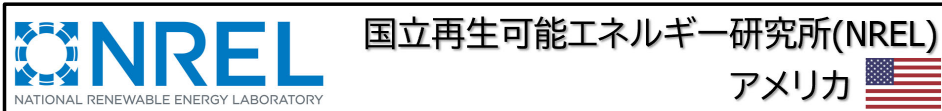
- ✓ 風力発電量の増産による電力システムや電力市場における風力発電の価値の最大化
- ✓ 風車のウェイク荷重の低減による、風力発電コストの低減化
- ✓ 風力発電所の制御モデルのベンチマークとベストプラクティスの開発、ベストプラクティス・データ交換の促進

# IEA Wind TCP Task44



## 主な参加機関

洋上風力研究に関する海外トップ大学/研究所が参画



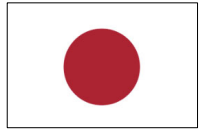
## 参加国

米国, オランダ, 英国, フィンランド, アイルランド,  
デンマーク, スペイン, ドイツ, ノルウェー, 日本



## 日本の体制

- 九州大学/内田 孝紀 (代表者)
- ジャパン・リニューアブル・エナジー, 4名
- 東芝エネルギーシステムズ, 3名
- 日立造船, 4名
- 東京ガス, 2名



2.4a Mini Symposia: Wind Farm Flow Control research organized by IEA Wind Task 44

WHEN 8:30am - 10:15am

TRACK Room 04 - Conference Room 2 (Level 3)



# Task44 ワークパッケージ(WP)

## Work Package 1

Track the evolving state of the art in wind farm control through collection of research results and expert elicitations

Develop set of recommendations and best practices

研究成果の収集

## Work Package 2

Characterize and quantify sources of uncertainties

Develop methods for estimating AEP/loads with overall uncertainty

Develop set of recommendations and best practices



## Work Package 3

Characterize the building blocks which define wind farm control

Build an overview of available options, specifications and assess TRL of each

Give a full landscape of the solution space

技術・アルゴリズムの開発

## Work Package 4

Collaborate and coordinate with other IEA Tasks and other wind farm control R&D activities

Based on tasks 1-3 and external projects, identify research gaps

Develop research roadmap

他のプロジェクトとの連携

メインにWP2へ参加

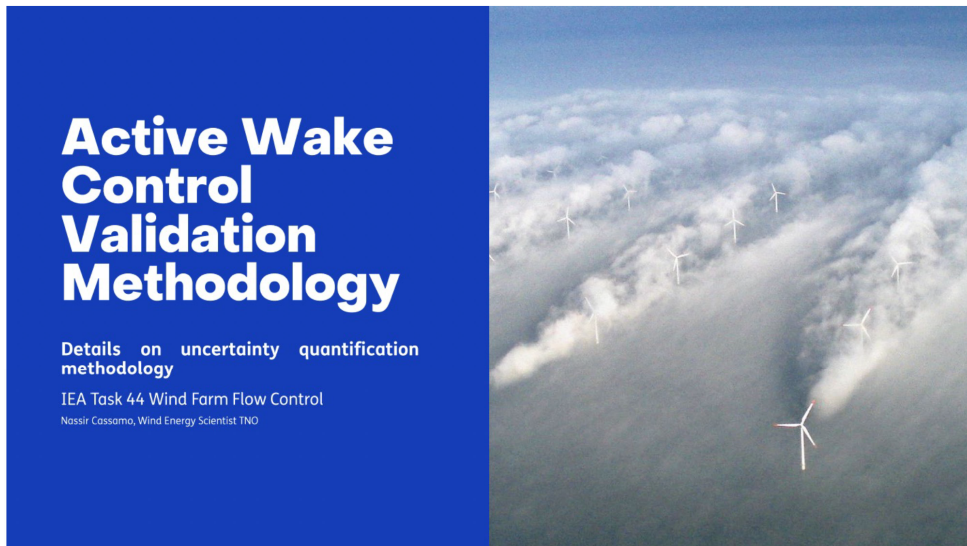
**Uncertainty Quantification / 不確実性の定量化**

# WP2 活動状況

- Monthly meetings
- “Review and Best Practices” papers

Review and best practices for wind farm control field validation

- Presenting at a monthly meeting!



- MTG\_20220523
- MTG\_20220531
- MTG\_20220615
- MTG\_20221208
- MTG\_20230201
- MTG\_20230301
- MTG\_20230425
- MTG\_20230627
- MTG\_20230725
- MTG\_20230926
- MTG\_20231024
- MTG\_20231113\_GeneralMTG
- MTG\_20231129

IEA Task44 WP2 Monthly Meeting 議事録		
プロジェクト	IEA Task44	
開催日時	2023年7月25日(火) 23:00-24:00	
場所	Microsoft Teams	
出席者(順不同/敬称略)	東京ガス 東芝 ESS	村上 深谷
議題	1. discussing and coordinating work on the paper "Review and best practices for wind farm control field validation." 2.	

■議事項目

1. discussing and coordinating work on the paper "Review and best practices for wind farm control field validation."

発表者: Eric Simley@NREL

- Task44 メンバーで執筆中の論文の構成や、各章の担当者などに関する議論。
- 論文の構成は以下:  
タイトル: Review and Best Practice for Wind Farm Flow Control Filed Assessment  
1章: Introduction  
2章: Overview of Field Validation Method for Wind Energy Application  
3章: Review of Wind Farm Control Field Validation Experiment  
4章: Recommendation for Filed Validation of Wind Farm Flow Control  
5章: Demonstration of Filed Validation for Example Wind Plants  
6章: Conclusion
- IEA Wind Task 44 Wiki のリンクが以下に変更  
<https://ieawindtask44.tudelft.nl/>

以上



Monday, November 13, 2023 11:00 PM (JST)

# IEA Task 44 General Meeting - Fall 2023

Paul Fleming, Task 44 Operating Agent  
(paul.fleming@nrel.gov)

Task 44 General Meeting

12:44

制御する ポップアウト チャット 参加者 手を挙げる リアクションする 表示 その他 カメラ マイク 共有 退出

NP Post, Natha... すべて表示

この会議で (34) 全員をミュート

UCHIDA TAKANORI

AG Adrien Guilloire (外部) 外部

BS Bose Sumantraa

EB Bossanyi, Ervin (外部) 外部

BF Breiffni Fitzgerald (外部) 外部

CN Cassamo Nassir (... (外部) 外部

DR David Robb (外部) 外部

DT DUC Thomas (E... (外部) 外部

EK Elie KADOICHE

PF Fleming, Paul (外部) 外部

JF Frederik, Joeri (外部) 外部

HH Hadi Hoghooghi (外部) 外部

NH Hille, Nikolai (外部) 外部

IE Irene Eguinoa (ゲスト) 会議のゲスト

LL Landberg, Lars (外部) 外部

L liu

WIND FARM FLOW CONTROL  
IEA Wind Task 44  
General Meeting  
13 November 2023

Technology Collaboration Programme  
by IEA





**IEA Wind Task 44 Talks** ①  
 @ieawindtask44talks21 · チャンネル登録者数 161人 · 13本の動画  
 このチャンネルの詳細 >

ホーム 動画 コミュニティ

新しい順 人気の動画 古い順

**Reinforcement Learning: offline** 19:17  
 Try mix of random actions and actions from policy. It Update policy to increase reward (decrease cost) Slow offline training

**IF<sub>0</sub> CONTROL** 16:30  
 WFF  
 Advantages  
 - PPO2 to address coupling  
 - Higher order models  
 - Direct shaping of frequency response for stability  
 - Transfer functions

**Results** 21:01  
 Uncertainty sweeping - PPI (sumath 0')

**Wake Mixing Dynamics: Applied to a PWT** 19:03  
 - Wake Interactions in Open-Field  
 - LES/CFD/Model based on Turbine Spacing  
 - Design Point and Wake coverage of Borealis turbines  
 -  $\sigma^2 \propto \frac{1}{x^2} \propto \frac{1}{B^2} \propto \frac{1}{\cos^2 \theta}$   
 - Design frequency response function, from data with angle to design wake

**Christiane Adcock - Differentiable Predictive Control for Dynamic Wake Steering** 149 回視聴 · 1 年前

**Aóife Henry - A Robust Auto-Tuning Procedure for Wind Turbine Individual Pitc...** 176 回視聴 · 1 年前

**Johan Meyers - Towards LES-based optimal control of wind farms** 273 回視聴 · 1 年前

**Daniel van den Berg - How dancing floating wind turbines can alleviate turbine wake...** 310 回視聴 · 1 年前

**Wind Model** 18:39  
 WECC

**Adam Stock - StrathFarm: A Demonstration of the University of Strathclyde Wind Farm...** 148 回視聴 · 1 年前

**Eric Simley - Results from a Wake Steering Experiment at a Commercial Wind Plant** 168 回視聴 · 1 年前

**Robert Braunbehrens - Wind farm as a sensor: Improving FLORIS predictions with...** 176 回視聴 · 1 年前

**Christopher Bay - FLORIS v3.0: Speed-ups and the new Cumulative-Curl model** 414 回視聴 · 1 年前

**New optimization algorithms** 29:29  
 - Serial Refine for yaw optimization

**Sebastian Mulders - The limitations of state-of-the-art torque control strategies fo...** 197 回視聴 · 1 年前

**Michael Howland - Wind farm wake steering control under transient atmospheric...** 741 回視聴 · 1 年前

**Adrien Guilloire - The development of load surrogates models for wind farm control...** 295 回視聴 · 1 年前

**Nikhar Abbas - ROSCO: A reference controller for fixed and floating wind...** 956 回視聴 · 1 年前

**Comparison** 32:19

**Marcus Becker - FLORIDyn: Development of a fast-running dynamic wind farm model fo...** 446 回視聴 · 1 年前

<https://www.youtube.com/@ieawindtask44talks21>

**IEA Wind Task 44 Wiki**

Database of Field Experiment Research Results

**② IEA Wind Task 44 Wiki**

Wind farm information for wind farm control field experiments in the literature

Article	Controller type	Farm name	Number of turbines	Turbine spacing	Turbine manufacturer	Turbine type	Terrain
Borrasa (2015)	Induction Control	EWTW	5	3 B D	Nordex	2500 kW	Flat terrain
Fleming et al. (2017)	Wake Steering	Longyan Rudong Chaojiandi	26	7.0 - 14.3 D	Emulsion Energy	EN1134/1.2 MW	Offshore
Ahmad et al. (2018)	Induction Control	Sole du Moulin Viewx	7	3.0 D	Senvion	MM2-2050 kW	Flat terrain, countryside
Fleming et al. (2019)	Wake Steering	Unknown	5	2.9 D - 5.0 D	Unknown	Unknown	Mix of flat and complex terrain
Howland et al. (2019)	Wake Steering	Summerview	6	3.5 D	Vestas	V10 1.8 MW and 2.0 MW	Flat terrain
van der Meek et al. (2019)	Induction Control	Goole Fields	16	2.3 D - 3.1 D	Senvion	2050 kW	Flat terrain
Simley et al. (2020)	Wake Steering	...	...	...	...	...	...
Fleming et al. (2020)	Wake Steering	Unknown	5	2.9 D - 5.0 D	Unknown	Unknown	Mix of flat and complex terrain
Simley et al. (2021)	Wake Steering	Sole du Moulin Viewx	7	3.7 D	Senvion	MM2-2050 kW	Flat with nearby forest
Fleming et al. (2021)	Wake Steering	...	...	...	...	...	...

<https://ieawindtask44.tudelft.nl/>

**③ LinkedIn**

**WIND FARM FLOW CONTROL**

**IEA Wind Task 44 - Wind Farm Flow Control**  
 Coordinating international research in the fields of wind farm flow control.  
 リサーチサービス · 104人のフォロワー · 51~200人の従業員

✓ フォロー中   ウェブサイトにアクセス

ホーム 概要 投稿 求人 従業員

**今後のイベント**

水 (2024年5月29日) 4:00  
**Task 44 General Meeting**  
 参加者3人

<https://www.linkedin.com/company/iea-wind-task-44-wind-farm-flow-control/>

# NEXT GENERAL MEETING

Planning to meet Tuesday, May 28th before the start of Torque



 **TORQUE 2024**

Florence - Italy

May 29th - 31st, 2024

166	:	22	:	12	:	2
DAYS		HOURS		MINUTES		SECONDS

## 風車ウエイク研究会：2021.4～2023.3



IEA Wind TCP Task44 との連携

## ウィンドファームの流れ場制御研究会：2023.4～2025.3

活動内容(2か月に1度をめどに開催)：■海外の動向調査 ■国内の情報共有 / 情報発信

研究会名称	ウィンドファームの流れ場制御研究会	
研究の目的, 期待される成果	IEA task 44 のウィンドファームの流れ場制御(Flow Farm Control)では、風力発電所の制御アルゴリズムと性能向上への貢献を目的とし、風車ウエイクステアリング手法等が議論されている。日本からも内田が代表者となり、数名の委員登録の下、task 44 に参加している。今後、国内の洋上風力発電分野においても task 44 で議論されている研究開発が重要になってくる。そのため、本研究では IEA task 44 の国内チームと連携を図りつつ、最新の風車ウエイク研究について調査を行う。また同時に国内の風車ウエイク研究についても情報交換を行う。	
体制		
主査/副主査	会員氏名	所属
主査	内田孝紀	九州大学応用力学研究所
副主査	鈴木章弘 / 谷垣洋一郎	(株) 風力エネルギー研究所
年月	内容	費目・予算
2023年3月	メンバー公募	
2023年4月	研究会発足	
2025年3月	学会誌特集号投稿	

# 海外の最新動向

Wednesday July 7<sup>th</sup> 2021

## Smart wind farms

Jan-Willem van Wingerden

※ Task44のOperating Agent



TWIND, Delft, The Netherlands

Full professor TU Delft, DCSC,  
Data Driven Control, Wind Turbine  
and Wind Farm Control

(Lab HP) <https://www.janwillemvangerden.nl/>



### Wind farms that can reduce the effect of wakes

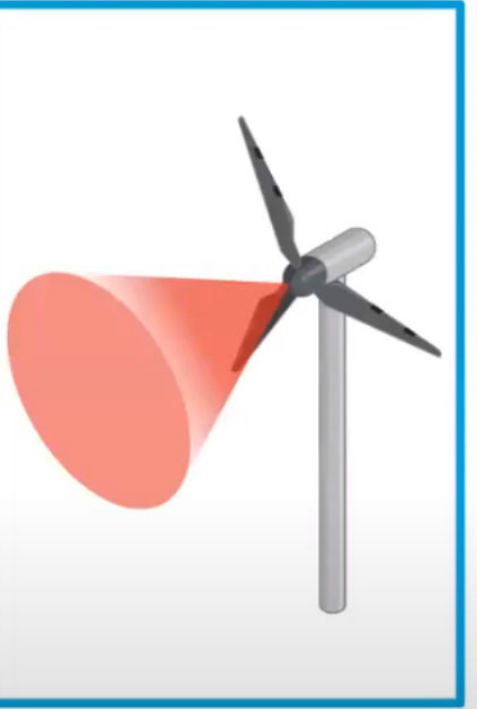


- The main objective is to get more energy out of the wind farm, but also taking into account that we don't want to increase the loading too much on the individual turbines.
- We typically build a first principles model. But the first principle model doesn't capture all the dynamics of a real wind farm or a real wind turbine.
- So what we believe is that we always have to augment our model with measurements. And again, we use here the data driven control approach.

Quote source: TWIND Summer School - Session\_Morning\_07\_07  
More info: <https://twindproject.eu/>

TWIND aims to create a network of excellence that will dynamize a pool of specialized research professionals and trainers in the domain of offshore wind energy.

## Lidar (sensors)



Reconstruction wind field



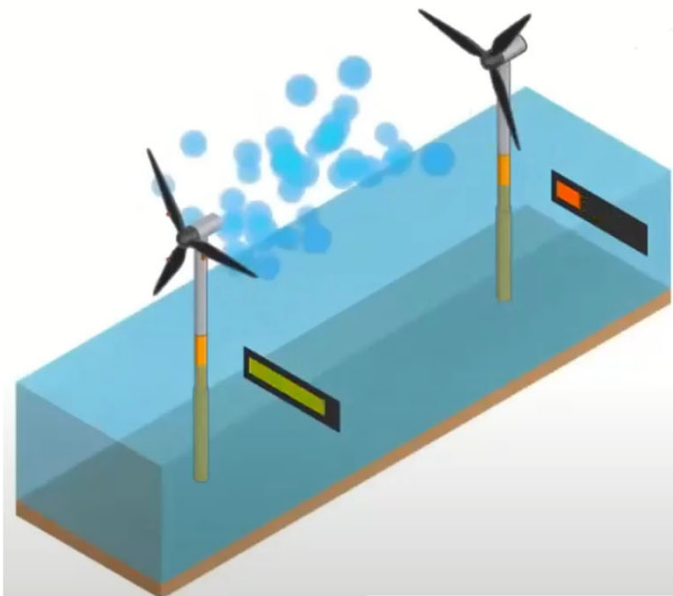
Prediction wind field



Real-time optimization

- In reality, we don't have access to the flow information. So the only thing that we have is measurements. So we only have measurements on a turbine level.
- So what we have to do if we want to do wind farm control and maybe this repositioning (floating). And we have to reconstruct the wind field.
- Then if we have the wind field we have to predict what's going on.
- And then we have to optimize. And then we can do a repositioning (floating). But we can also use already existing control technology on a turbine to maximize the energy capture and or to reduce the structural loading in the wind.

# Control Technologies



Quasi-steady flow control  
Axial-induction-based control

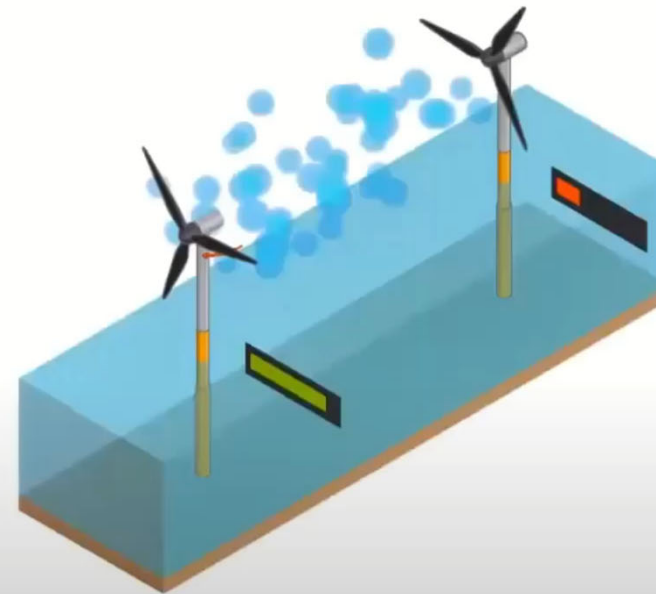
Static wake control concepts rely on affecting the wake through relatively slow changes of the control degrees of freedom of the turbine in a way that affect the time-averaged properties of the wake.

- Induction control (誘導制御) is basically derating (負荷低減).
- If we derate the first turbine, then it will let energy go. And then we hope that the energy that we let go will be picked up by the turbines in the wake.
- We hope that the sum of the energies will be bigger than the greedy approach.
- Now recent results basically show that actual induction control doesn't work. So the energy that we let go is not picked up by all the other turbines.
- High-fidelity wind tunnel and field tests have shown that the benefits of induction control are very limited.

# Control Technologies

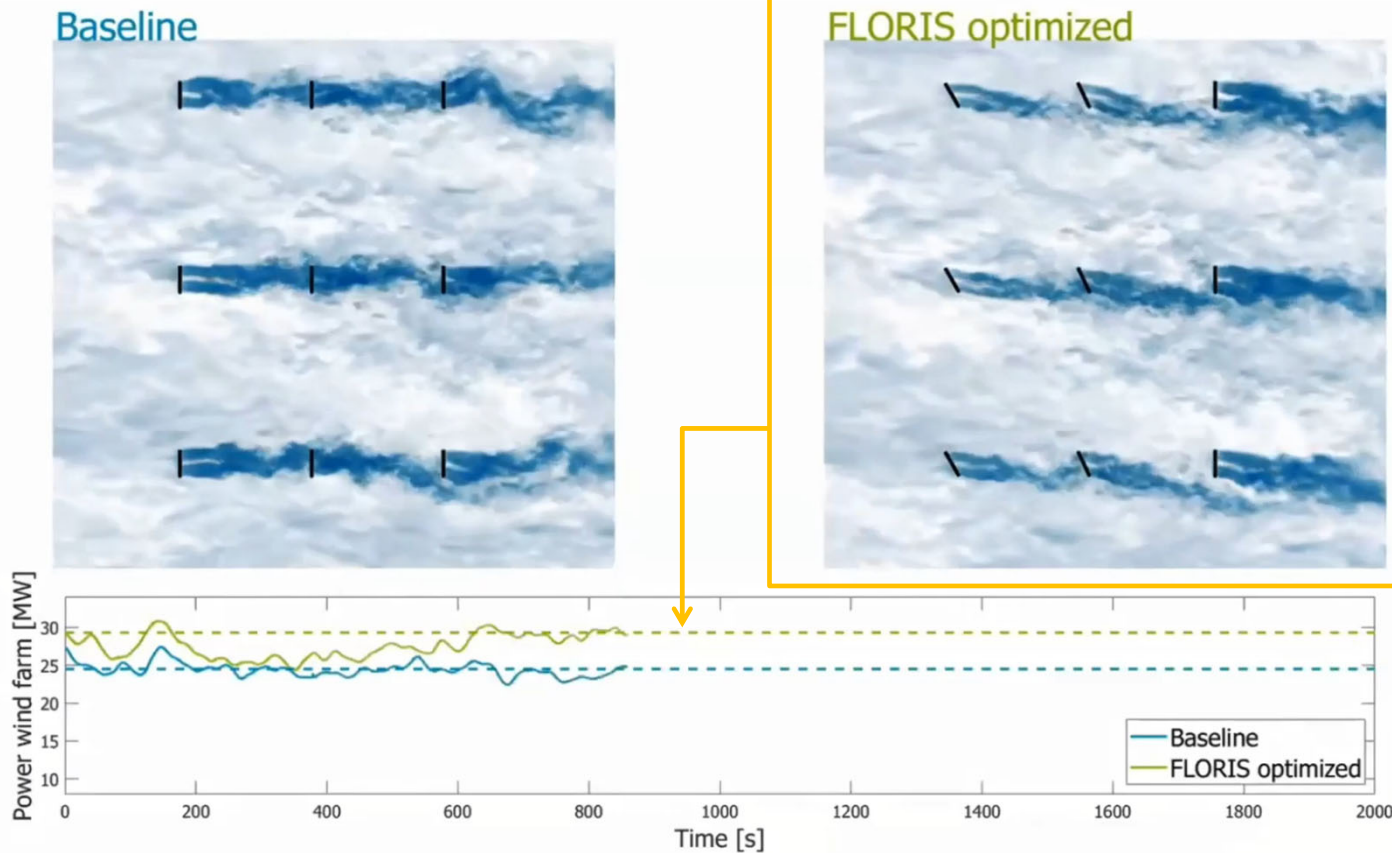
- On the other side, there is another existing control technology which is called wake steering.
- We misalign the first turbine with the main wind direction.
- If we misalign the turbine, we can redirect the wake. So what we try to do is that the wake doesn't hit the turbines downstream.
- This technology seems to have a lot of potential in wind tunnel experiments, high fidelity simulations, and field experiments.

Static wake control concepts rely on affecting the wake through relatively slow changes of the control degrees of freedom of the turbine in a way that affect the time-averaged properties of the wake.



Quasi-steady flow control  
Wake steering using yaw offsets

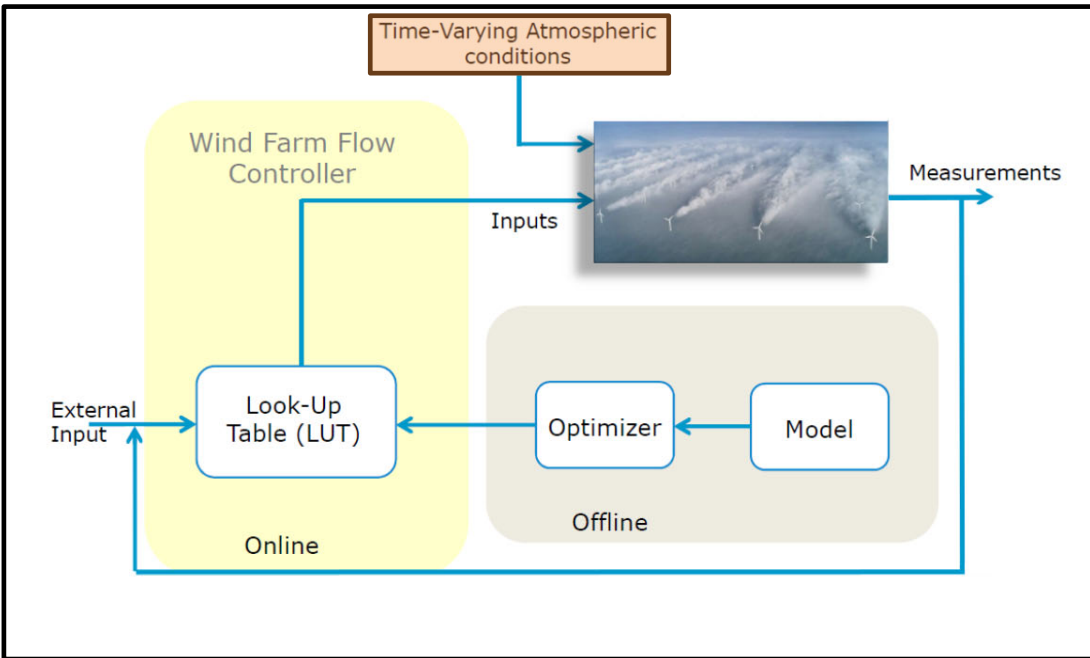
### Quasi-steady flow control Wake steering using yaw offsets



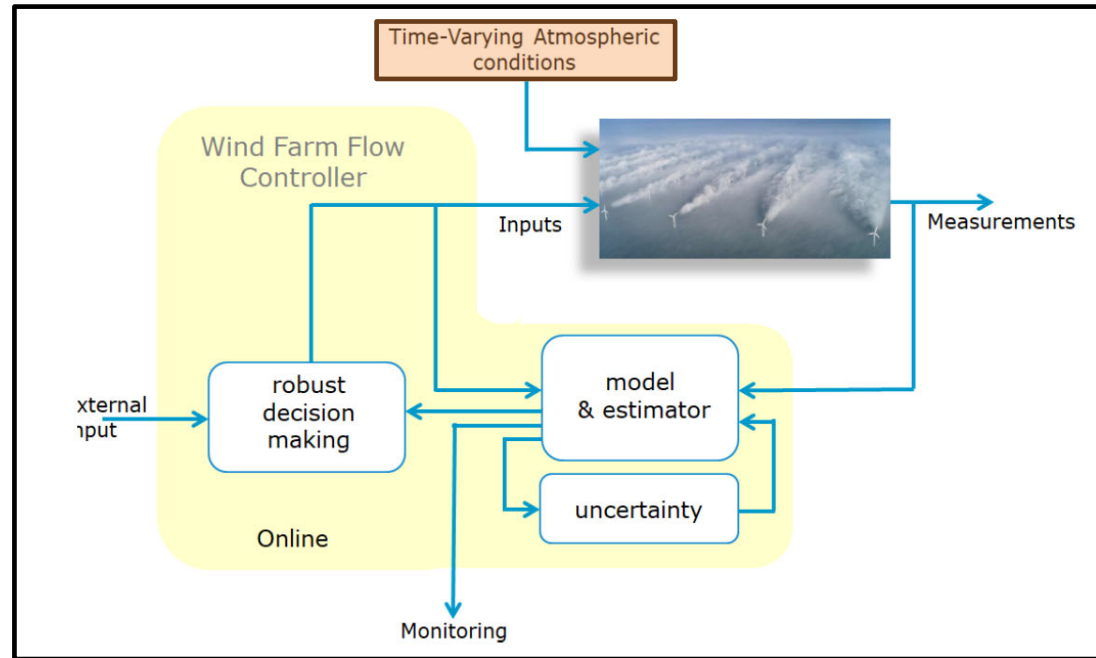
- At the left, we see the baseline. And at the right, we see the optimized setting.
- The optimized setting meaning that we had a first principles model, in this case the FLORIS.
- Then we optimized the optimal YAW settings. And what we nicely see is that we can do wake steering.
- Now in the graph, we can also see the potential and the amount of energy that we can now extract out of a wind farm (Of course, this is a high fidelity simulation).
- The wind conditions are more or less steady. It's the same inflow direction and also the turbulence intensity is more or less the same.
- So we believe that also if we really want to apply wake steering in a wind farm, we also have to make it more robust with respect to time varying conditions.



### Open-loop wind farm control scheme

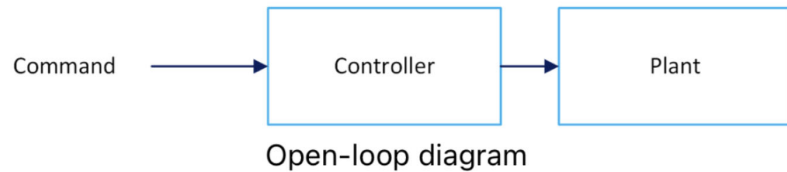


### Closed-loop wind farm control scheme



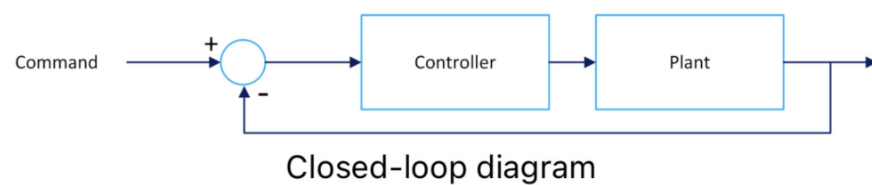
Key words : data driven approach, MPC (モデル予測制御) principle

### 補足



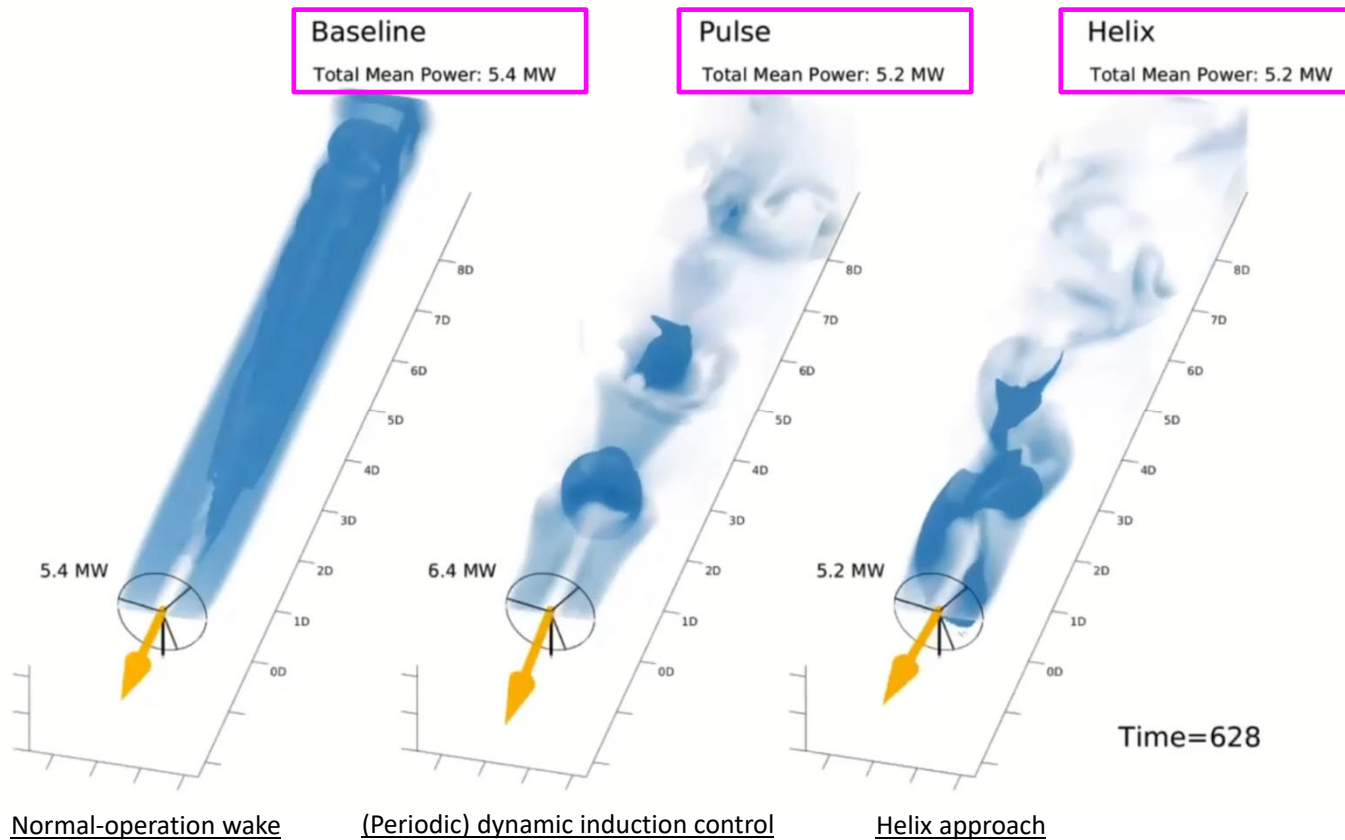
指令だけをしてフィードバックを取らない制御

(例)シーケンス制御：あらかじめ定められた順序に従って制御の各段階を逐次進めていく制御]



プラントの出力値(測定値)を出力し、それをフィードバックさせ、入力値と出力値を常に比較して両者を一致させるように全体の操作量を調整する制御

## Wake-Mixing

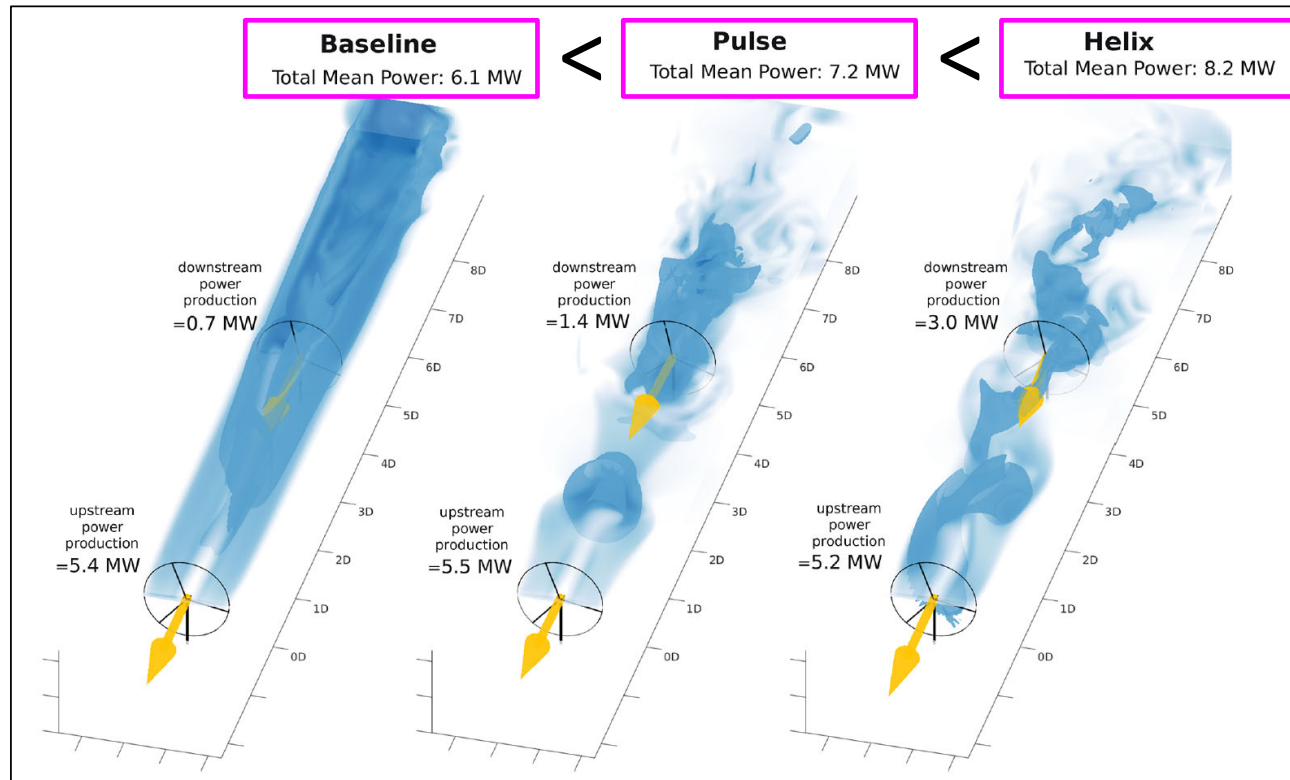


- Here, we focus on the challenges related to triggering and interacting dynamically with wakes and turbulence as a means to control wind farm flow and to speed up wake breakup or to increase mixing and entrainment into the wakes.
- Recently, some first studies suggest that this effect may be leveraged to significantly increase the energy extraction of wind farms.

Illustration from an LES study (SOWFA), 10MW Wind Turbine

Dark blue shading corresponds to an isosurface of the velocity;  
light blue shading in the horizontal plane corresponds to velocity magnitude.

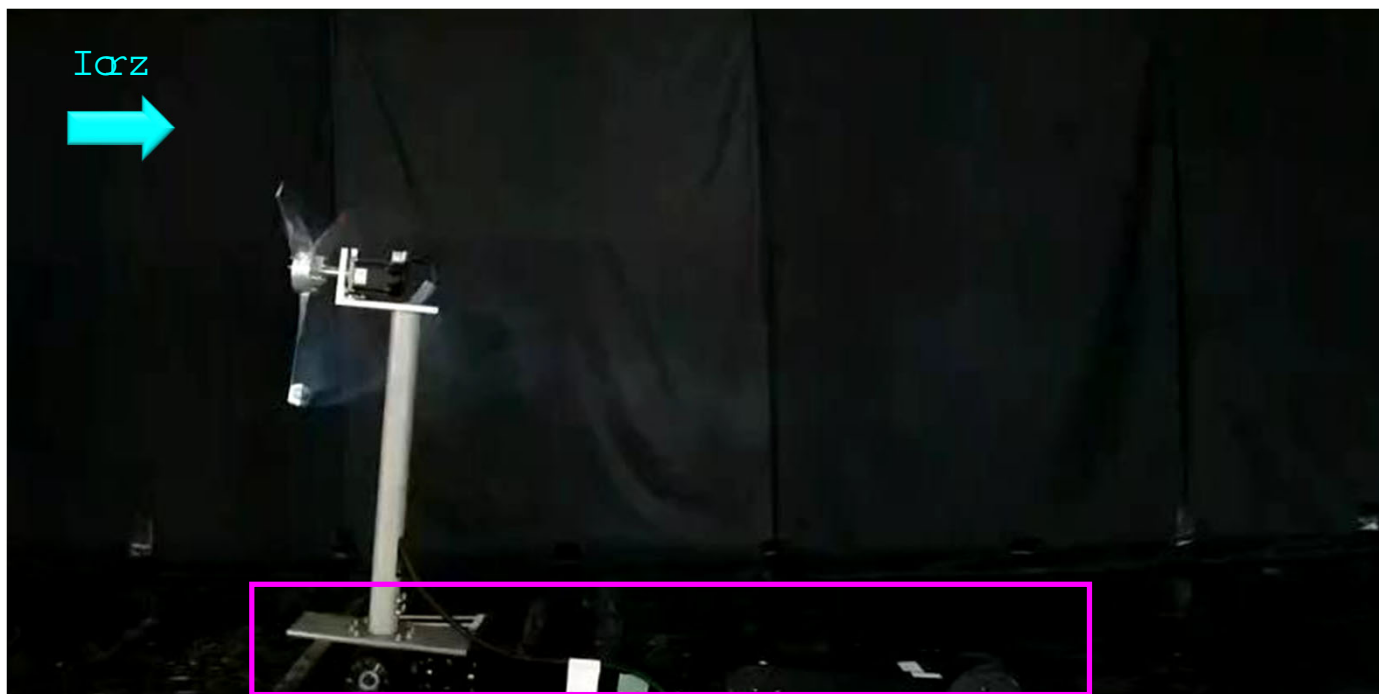
# Wake-Mixing



- However, then still you have to do all the safety checks and look at all the loads.
- So implementation wise, on paper it seems easy, but for industry it's quite a big step.

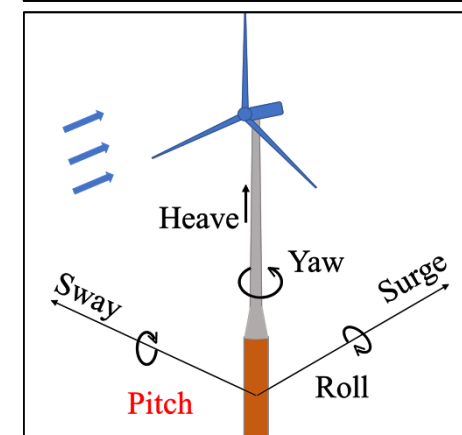
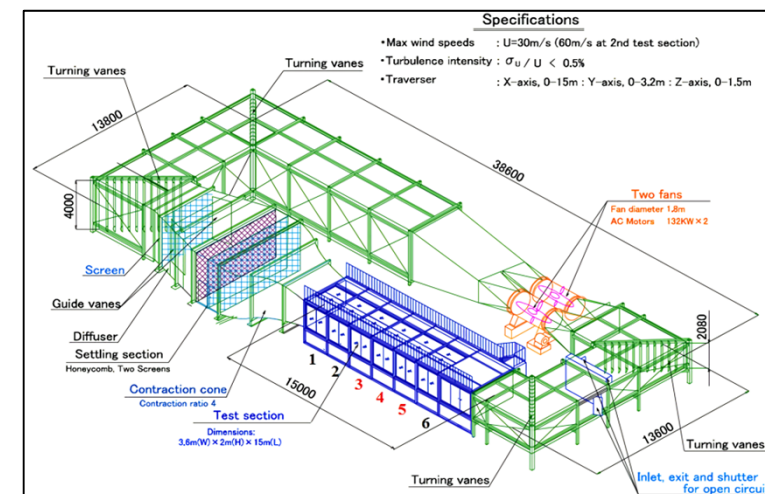
# Wake-Mixing

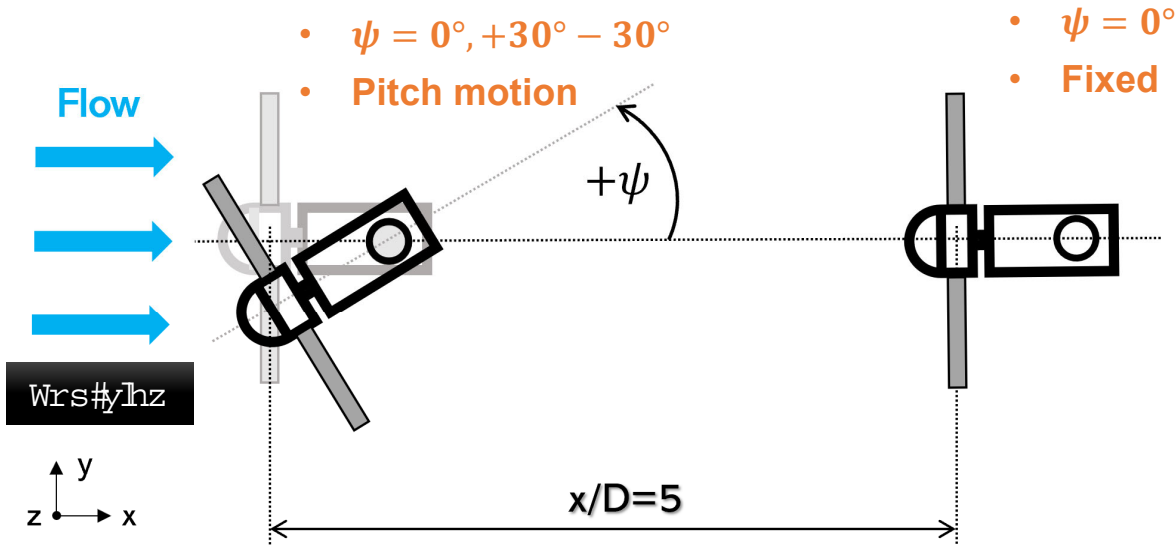
## 九州大学・内田研究室での取組



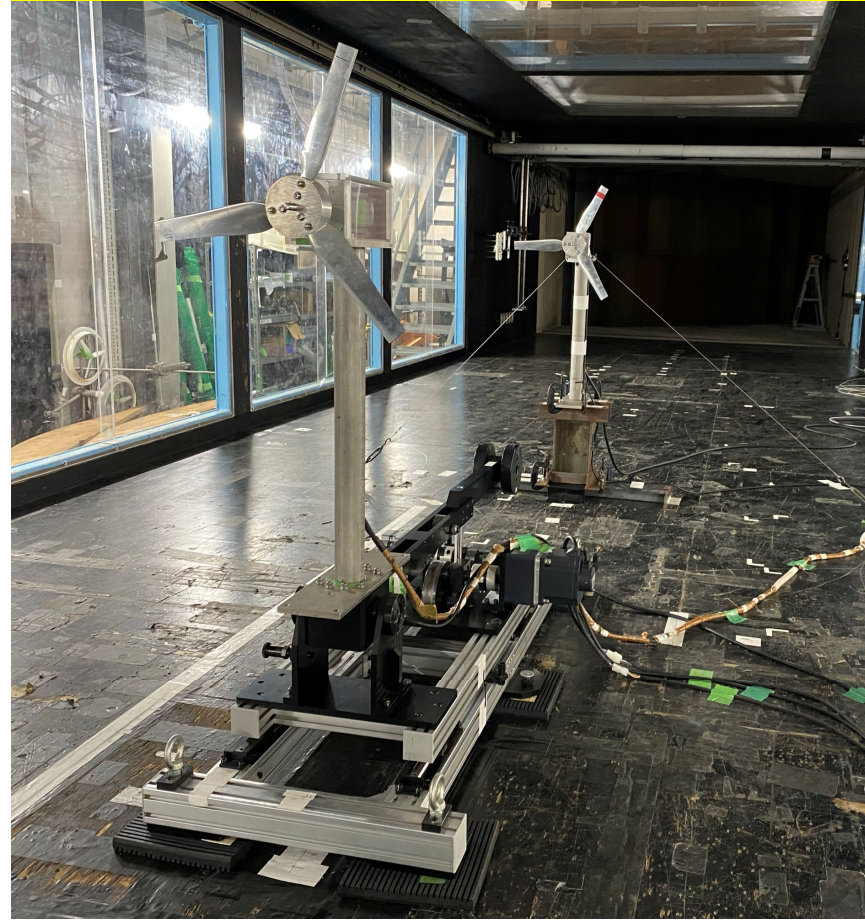
加振装置製作し、浮体の動揺(ピッチ運動)を再現

- Pitch motion amplitude:  $\pm 5$  [deg]
- Pitch motion period: 0.8 [s]

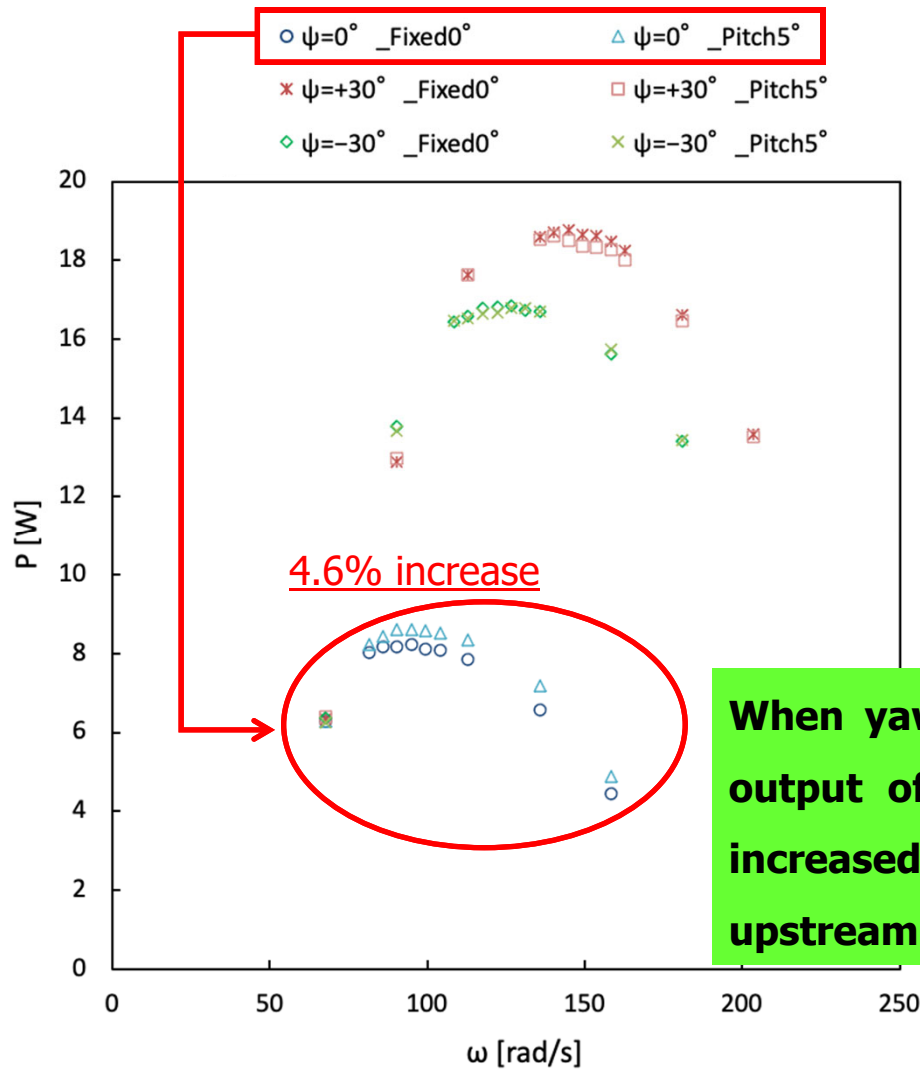




**The power generation performance of the wind turbine was evaluated by varying the blade rotation speed.**



Parameter	Value
Inflow wind speed [m/s]	10
Rotor diameter [m]	0.442
Tip speed ratio of the upstream wind turbine [-]	3.6
Rotor speed of the upstream wind turbine [rpm]	1556
Sampling frequency [Hz]	1000
Sampling time [s]	60
Pitch motion amplitude [deg]	±5
Pitch motion period [s]	0.8



- The power generation performance of the wind turbine was evaluated by varying the blade rotation speed.
- Torque was measured and power output was computed.

$P$  [W] : Power  
 $Tr$  [Nm] : Torque  
 $\omega$  [rad/s] : Angular velocity

When yaw angle is  $0^\circ$ , the power output of the downstream WT is increased by pitch motion of the upstream WT.

2022年

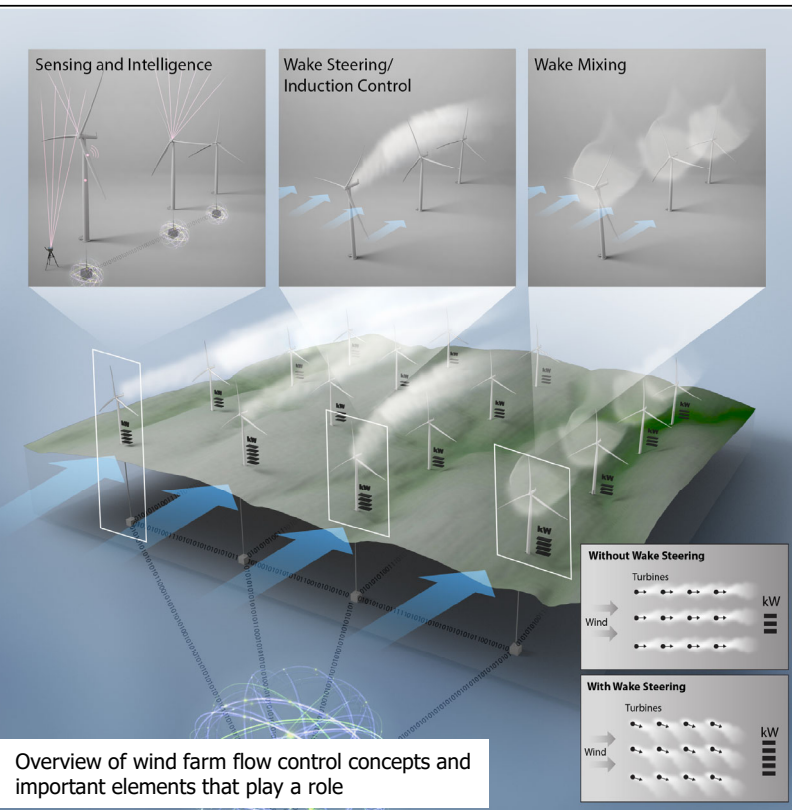
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## Wind farm flow control: prospects and challenges

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Wind farm control has been a topic of research for more than two decades. It has been identified as a core component of grand challenges in wind energy science to support accelerated wind energy deployment and transition to a clean and sustainable energy system for the 21st century.

風力エネルギー科学における壮大な課題の中核要素として特定されている。

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In summary, the field of wind farm flow control is an active area of research and innovation, with many interesting multidisciplinary challenges(※), and exciting prospects for the increase of the total value of wind energy for society.

※学際的な課題

### 1 Introduction

- 1.1 Main control objectives studied to date
- 1.2 Control approaches
- 1.3 Outline

### 2 Wind farm flow control physics: turbulence, wakes and the atmospheric boundary layer

- 2.1 Quasi-steady flow effects
  - 2.1.1 Axial-induction-based control
  - 2.1.2 Wake steering using yaw offsets
- 2.2 Wake dynamics and turbulence
  - 2.2.1 Wake dynamics
  - 2.2.2 Boundary-layer turbulence

### 2.3 Mesoscale effects, blockage and wind farm wakes

### 3 Control algorithms

- 3.1 Current practice — Open-loop control
- 3.2 The closed-loop paradigm
- 3.3 Synergies with artificial intelligence and other digitalization concepts
- 3.4 Controllability, observability, and sensors

### 4 Validation and industrial implementation

- 4.1 Proof-of-concept studies in high-fidelity simulation tools
- 4.2 Validation in wind tunnel experiments
- 4.3 Validation via field tests
- 4.4 Industrial implementation

### 5 Integrated design and systems perspective

- 5.1 Progress in wind farm design optimization research
- 5.2 Wind farm control co-design (CCD)
  - 5.2.1 Wind farm CCD for AEP and LCoE objectives
  - 5.2.2 Wind farm CCD for profitability objectives
  - 5.2.3 Wind farm CCD for non-economic objectives

### 6 Conclusions