

# IOES, Division of Offshore Wind Energy System

**International Joint Usage/Joint Research Promotion Workshop**  
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**Institute of Ocean Energy, Saga University**



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2. Researches on Optimization Methods
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6. Conclusion



# 1. Division of Offshore Wind Energy System

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## 1.1 Institute of Ocean Energy; IOES

### Ocean Thermal Energy Department

- Division of Ocean Thermal Energy Conversion
- Division of Innovation for Thermal Energy Conversion
- Division of Utilization of Deep Ocean Water

### Ocean Fluid Energy Department

- Division of Wave Energy
- Division of Tidal & Ocean Current Energy
- **Division of Offshore Wind Energy (OWES)**

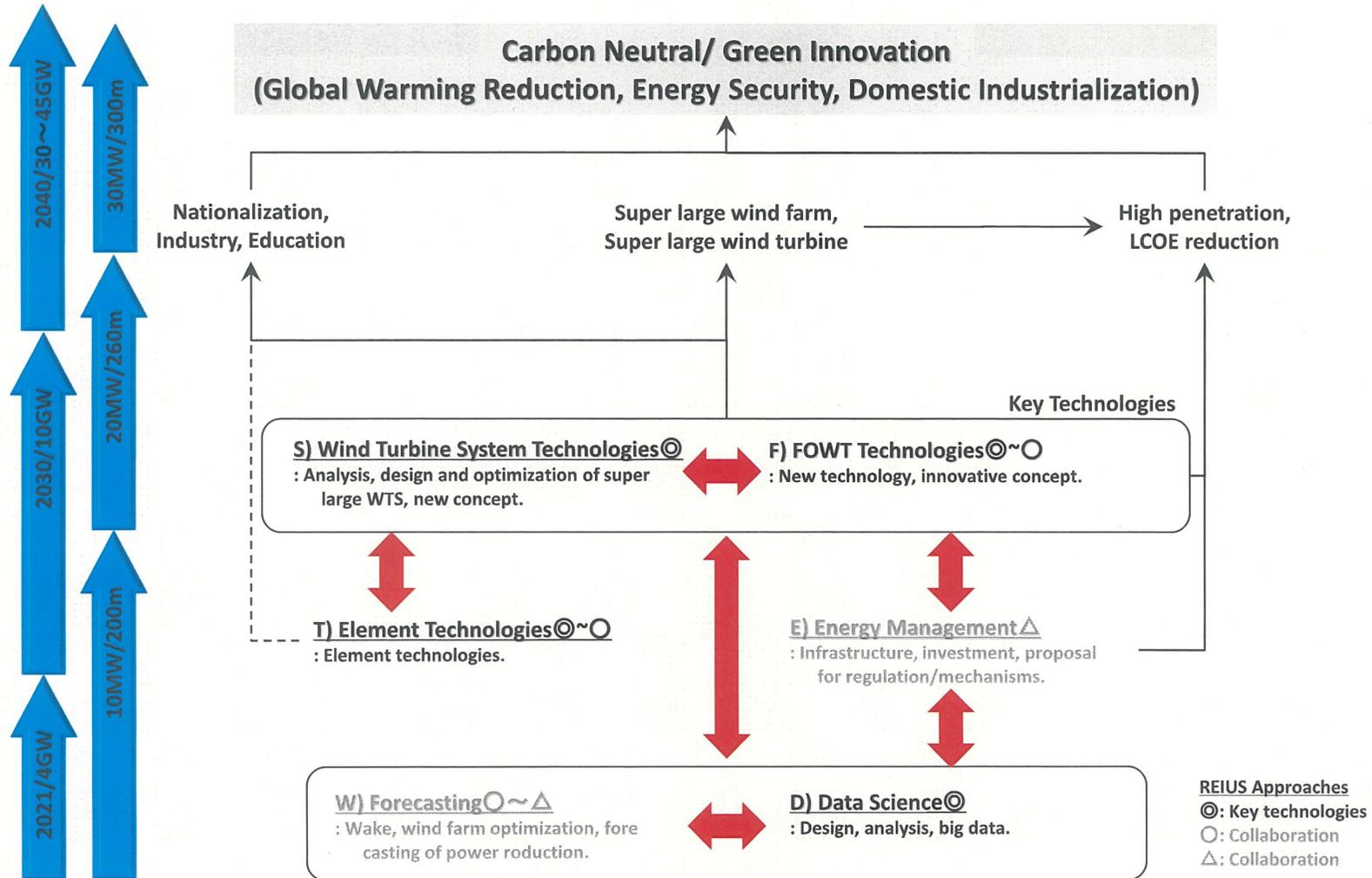
### Sea Water Resource Department

- Division of Marine Biochemical Resource Creation
- Division of Information and Environment for Ocean Energy
- Division of Ocean Energy Social Science
- Division of Comprehensive Ocean Energy Utilization
- Division of Human Resource Cultivation for Ocean Energy

<https://www.ioes.saga-u.ac.jp/>



# 1.2 Wind Energy Research Approaches of KU-REIUS/SU-OWES

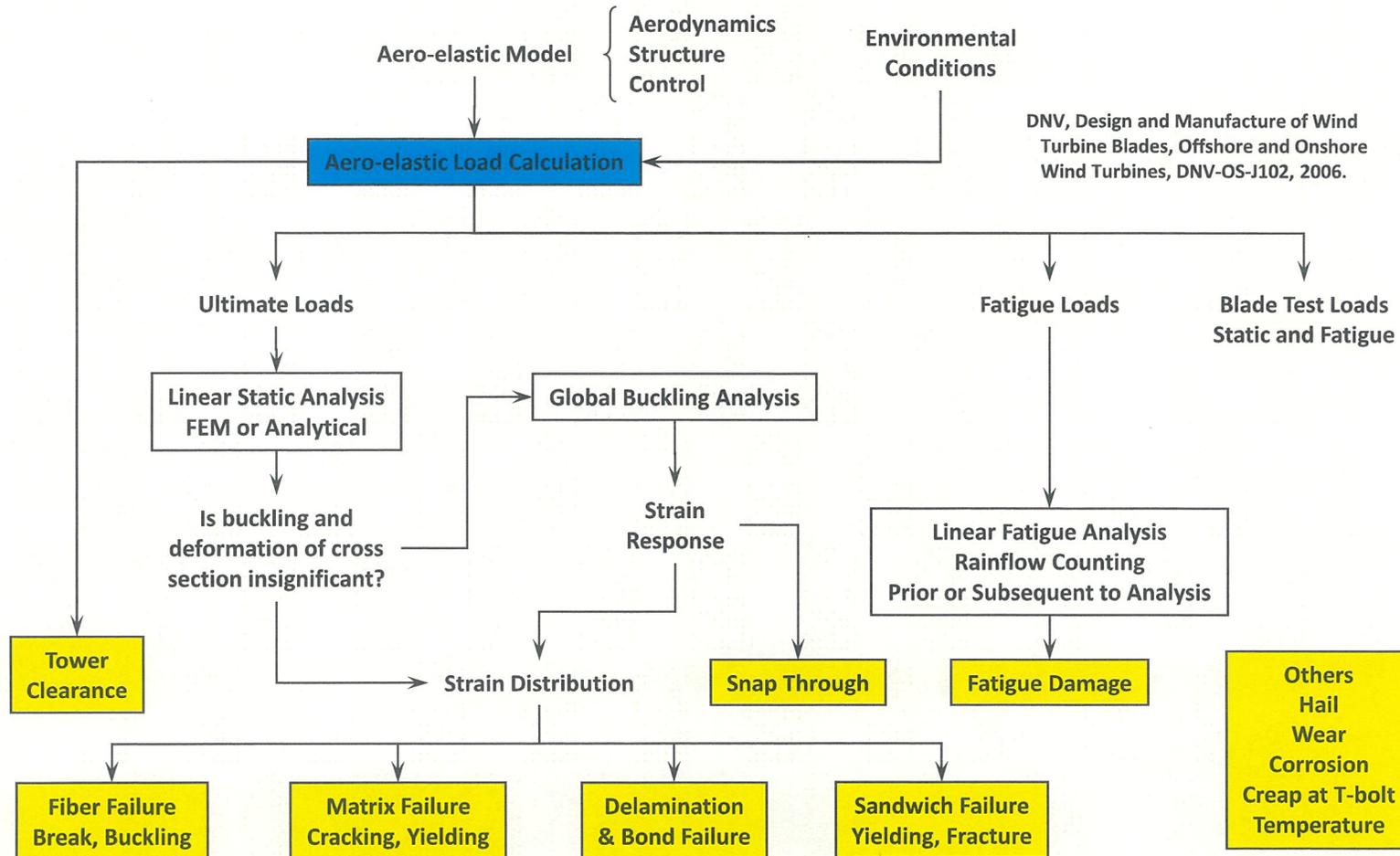




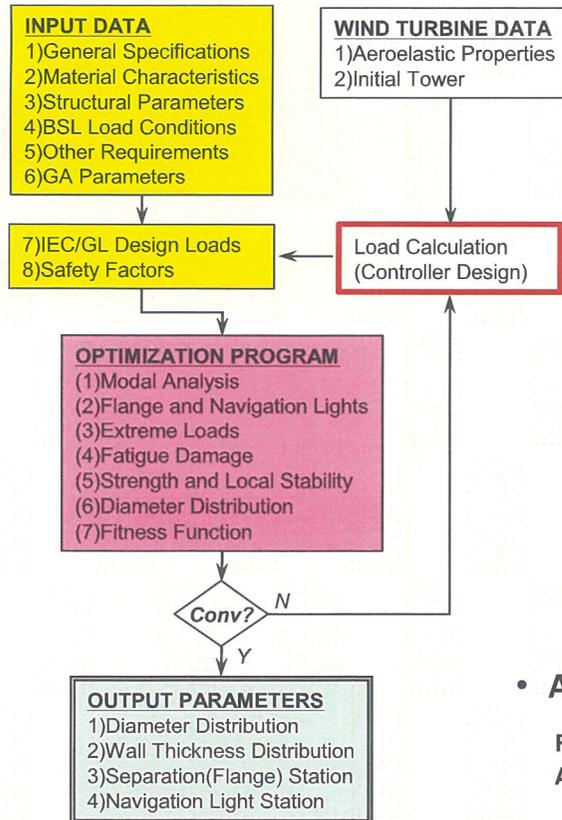
## 2. Researches on Optimization Methods

1. Division of Offshore Wind Energy System
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## 2.1 Design Flow (Blade)



## 2.2 Tower Optimization

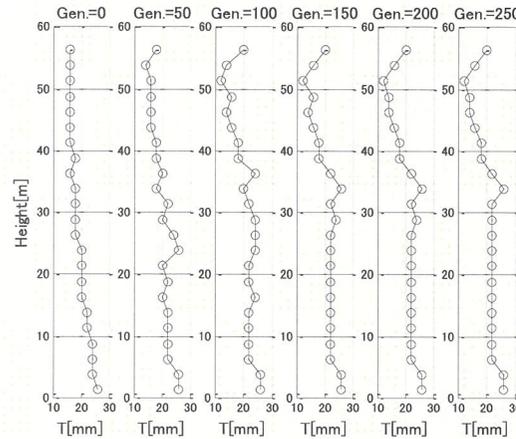


- Applied for 2MW WT.  
FY2006 Paper Award (Oshida Award), JSES, 2027.

$$\text{Cost function: } S = m_{\text{Tower}} \times (1 + p_1 + p_2 + p_3 + p_4 + p_5)$$

$m_{\text{Tower}}$ : Tower mass

$p_2 \sim p_5$ : Penalty functions



Wall thickness history



SUBARU 2.0MW

Item	Unit	A	B	C	D	E	F	G
Wind Class	-	1A	2A+	1A	1A	1A	1A	1A
BSL Basic Wind Speed	m/s	38	38	38	38	38	38	38
BSL Earthquake	m/s <sup>2</sup>	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Top Dia.	m	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Base Dia.	m	4.2	4.2	3.7	4.2	4.2	4.2	4.2
Deviation	m	32.5-35	35-37.5	40-42.5	NA	40-42.5	35-37.5	35-37.5
Material	-	SM490	SM490	SM490	SM490	SS400	SM490	SM490
Structural Damping Ratio	-	0.005	0.005	0.005	0.005	0.005	0.1	0.005
Wall Thickness Step	mm	2	2	2	2	2	2	1
Wall Thickness Range	mm	12-26	12-24	12-24	12-26	14-26	12-24	11-25
Variety of Thickness	-	8	7	7	8	6	7	12
Max. Piece Mass	t	40.4	41.2	40.0	40.9	40.6	41.3	41.8
Max. Piece Length	m	22.5	20.0	15.0	22.5	22.5	20.0	22.5
Number of Separation	-	3	3	4	3	4	3	3
1st Bending Freq.	Hz	0.446	0.413	0.436	0.443	0.428	0.439	0.439
Tower Mass	t	107.0	97.2	114.3	104.8	108.4	100.8	103.1
Mass Deviation	t	0.0	-9.8	7.3	-2.2	1.4	-6.2	-3.9

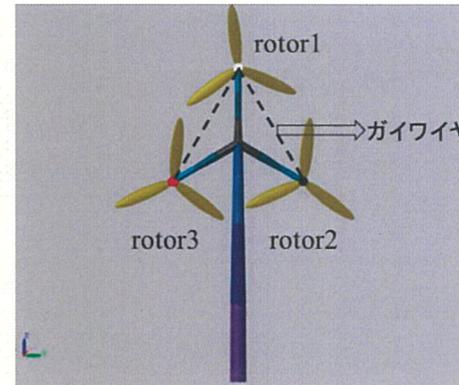
## 2.3 Multi-rotor System: Design and Analysis Methods

### Outlines

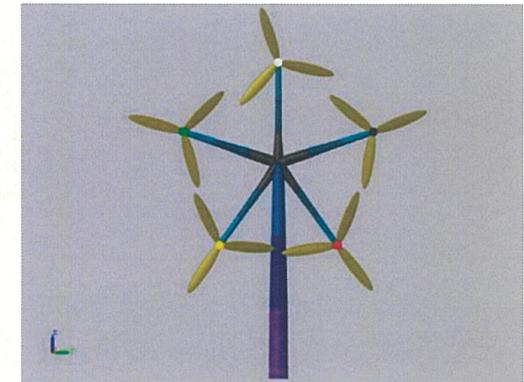
- Development of MRS, which is promising future super-large wind turbine concept as matured (cost and quality) WTs are applicable.

### Results

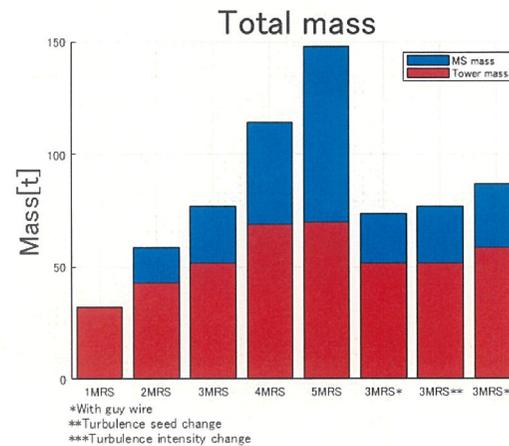
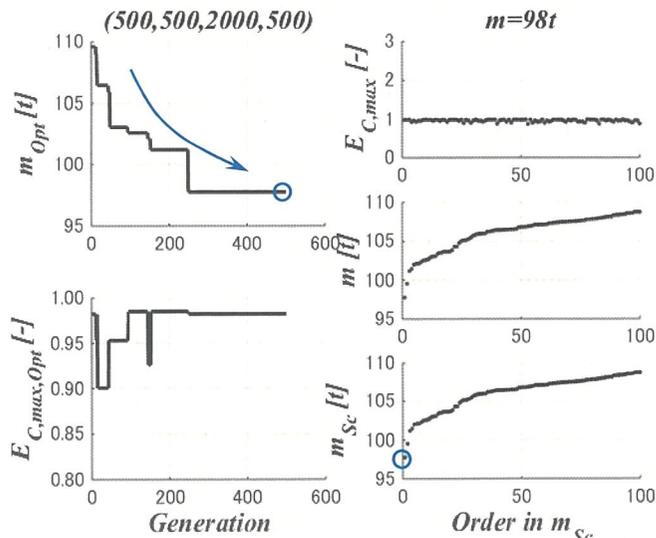
- 1) Modal method code.
- 2) Multi-body-dynamics code.
- 3) Tower optimization code (diameter and thickness).



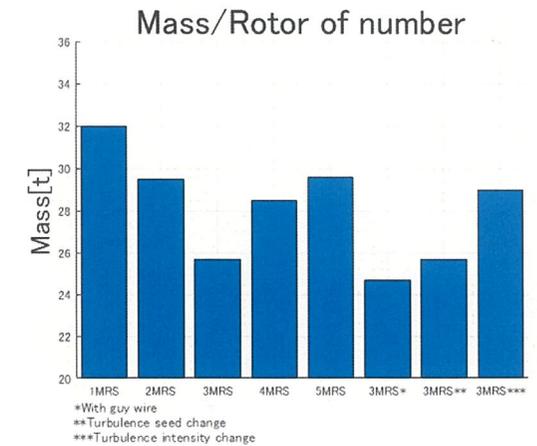
3MRS (guy wire supported)



5MRS



Mass of support structure



Mass per rotor



### 3. Researches on Downwind Turbine Technologies

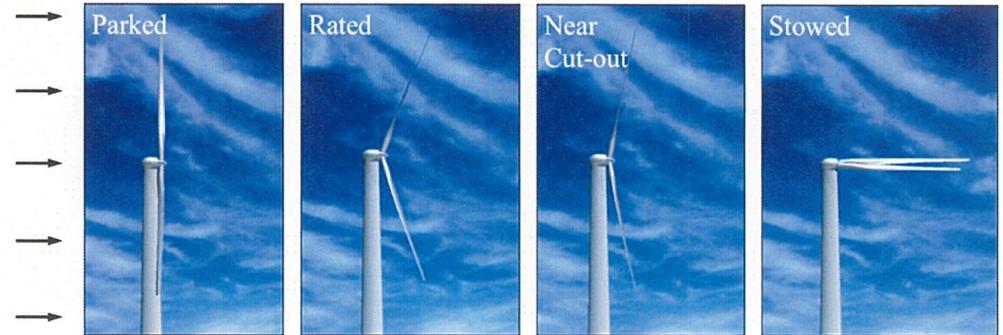
1. Division of Offshore Wind Energy System
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### 3.1 Downwind Turbines

- Almost all modern wind turbines have upwind rotors.
- However, some innovative concepts assume downwind rotor.
- Downwind turbines have some promising features; scaling merits and floating turbines.
- One of the major technical problems is the blade-tower aerodynamic interaction (tower shadow effect).



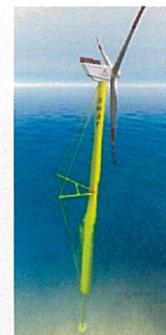
Ref. Doque, P.M., *Windpower Engineering and Development*, Sep 28, 2009.



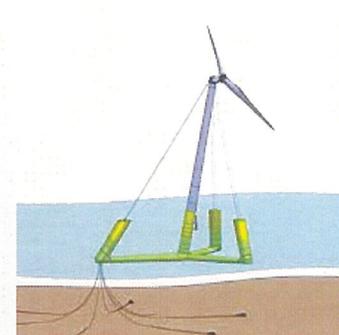
SUMR Concept [NREL]



Hitachi 2MW [Toda Corp]



SWAY



OPTIFLOW 6MW [NEDO]



X1Wind [X1Wind]

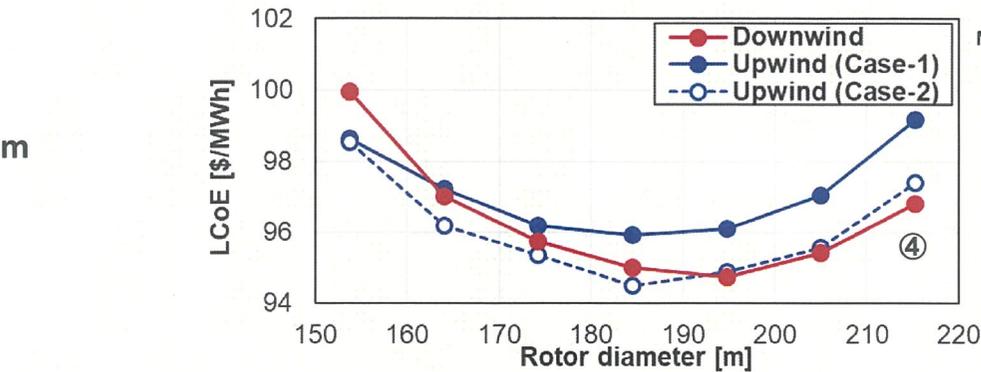
## 3.2 Scaling Merit of Downwind Turbines

### Conditions (10MW, Wind Class: 1A)

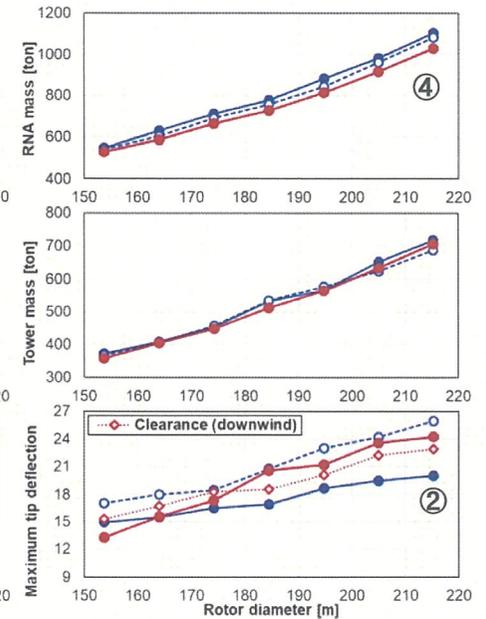
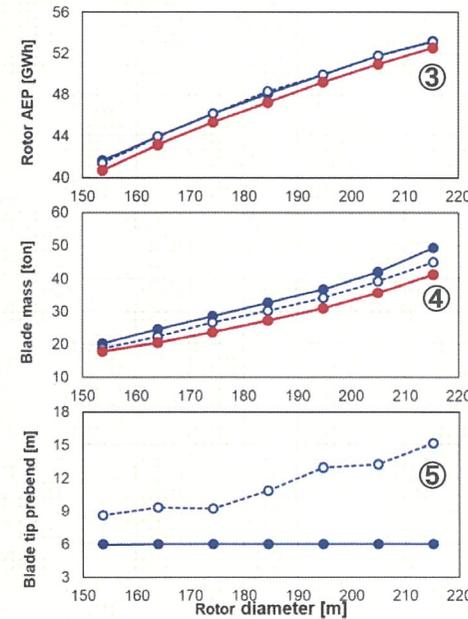
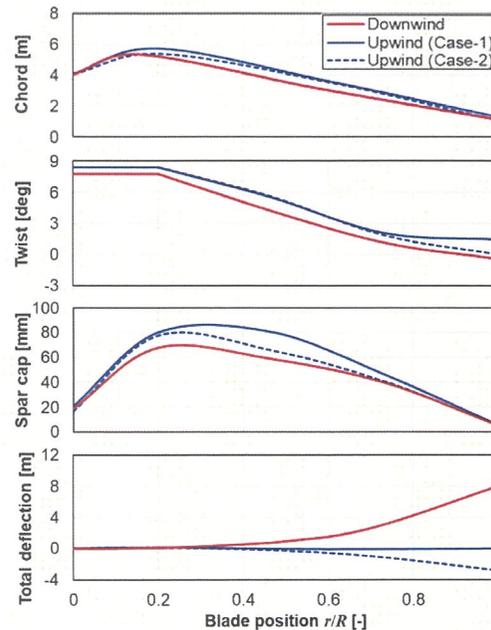
- Downwind: Pre-bent = 0m
- Upwind -1/-2: Max pre-bent =6 m/20 m

### Results

- ① Downwind rotor is promising for super-large WTs due to more flexible lighter blades.
- ② Upwind turbine blades should be stiffer and/or have pre-bending.
- ③ Downwind turbine shows smaller AEP as the blade deformation makes the rotor area smaller.
- ④ The lighter blades of downwind turbine make the nacelle lighter, result in lower LCOE.
- ⑤ Advantages of downwind rotor will be larger in cases the cost of pre-bent blade is considered.



Namura, N., Shinozaki, Y., Design Optimization of 10MW Downwind Turbines with Flexible Blades and Comparison with Upwind Turbines, J.Phys.: Conf. Ser. 1618 042021, 2020.



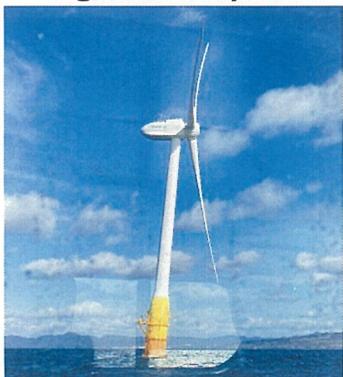
### 3.3 Alignment Merit of Downwind Turbines for FOWTs

#### Rotor Alignment by Floater Inclination

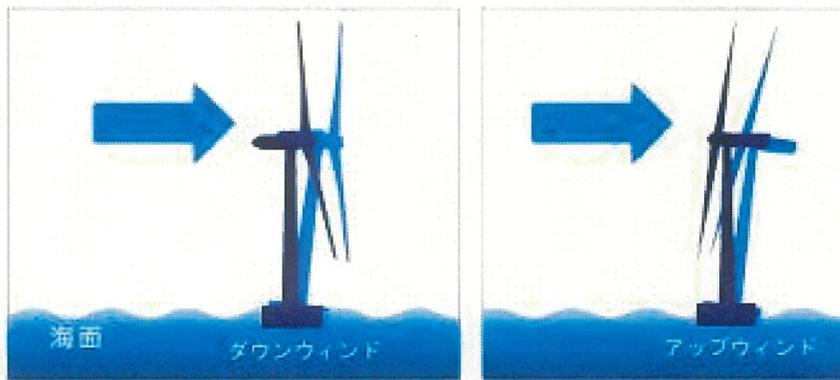
- Horizontal axis wind turbines have tilt angles to keep the rotor-tower clearance.
- Floaters incline downward in power production by the rotor thrust, which change the rotor-wind misalignment.

#### Estimation

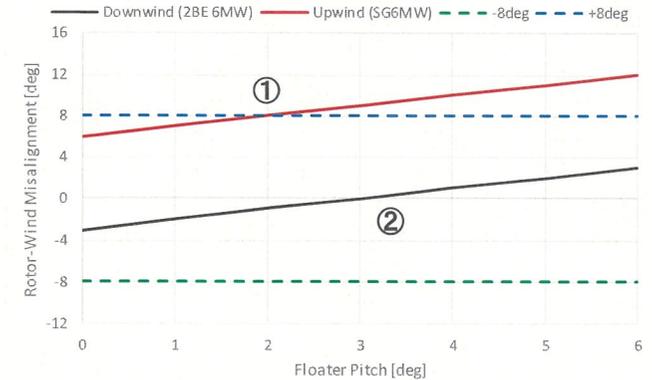
- Downwind: 2B Energy 6MW (Tilt=-3deg)
- Upwind: SGRE 6MW (Tilt=+6deg)
- Rotor misalignment: ①Upwind rotor surpass 8deg with 2deg of inclination. ②Downwind rotor is below 3deg in 0~6deg of floater inclination.
- Inflow power (at +3deg of floater inclination): ③Downwind rotor is 3.6% larger than upwind.



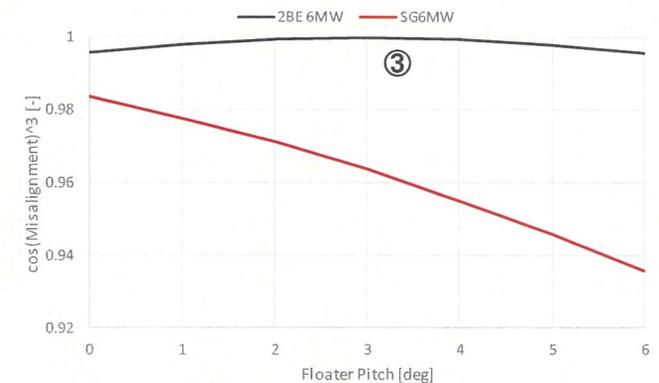
Goto 2MW in power production



Rotor misalignment in floater inclination

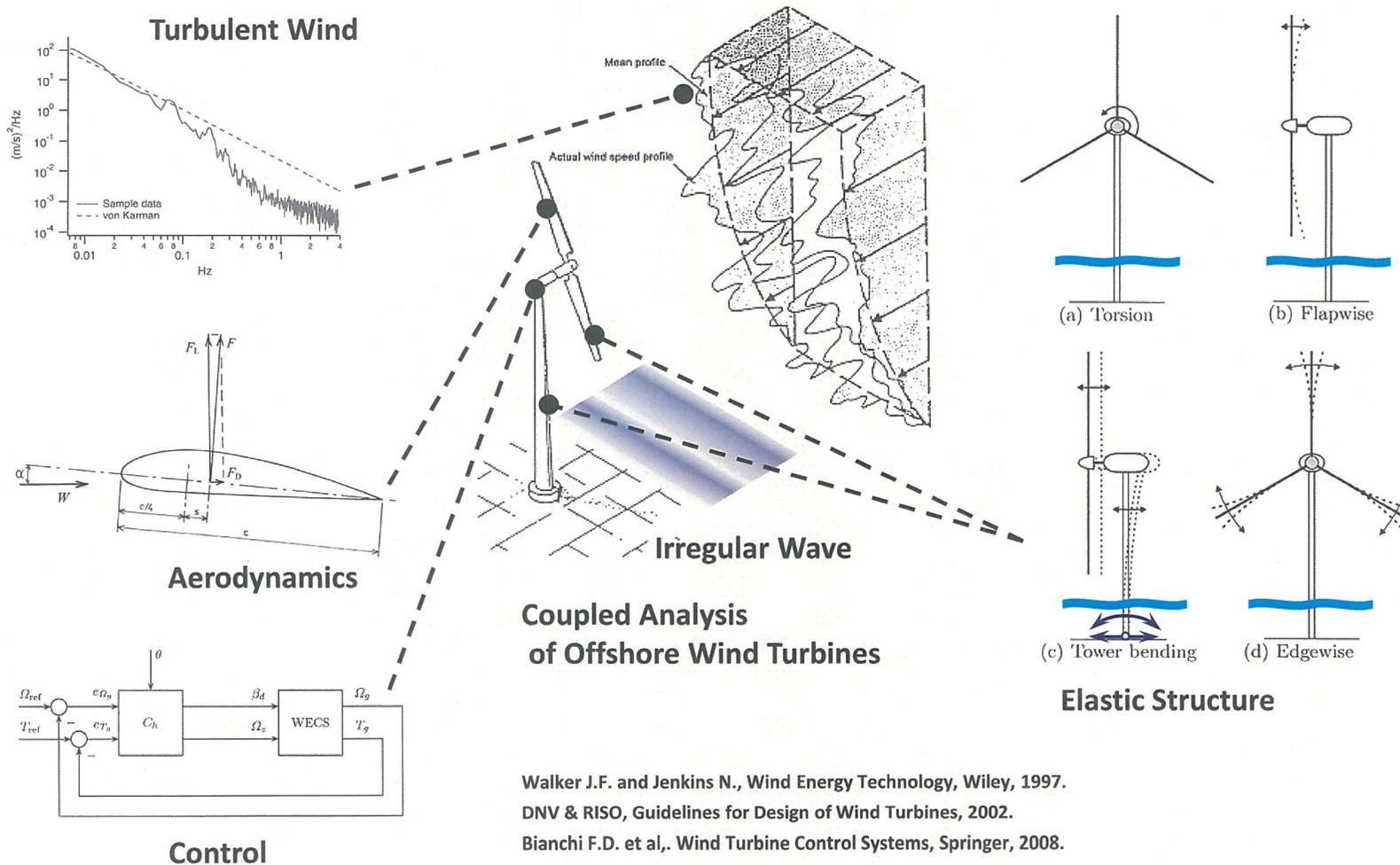


Rotor misalignment to floater inclination



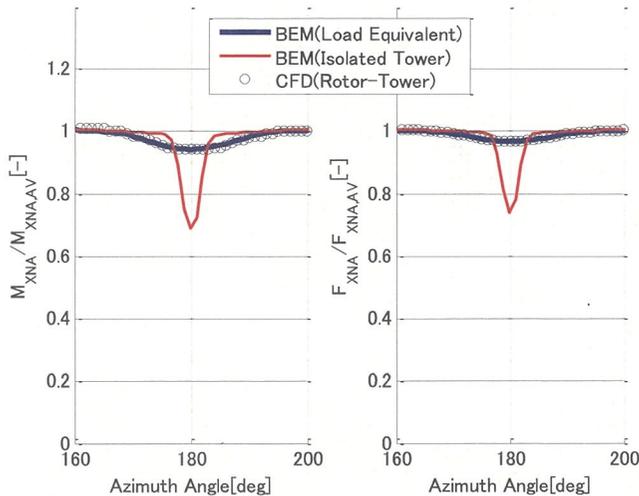
Relative inflow power to floater inclination

### 3.4 Aero-servo-elastic Analysis of Bottom Fixed WT's

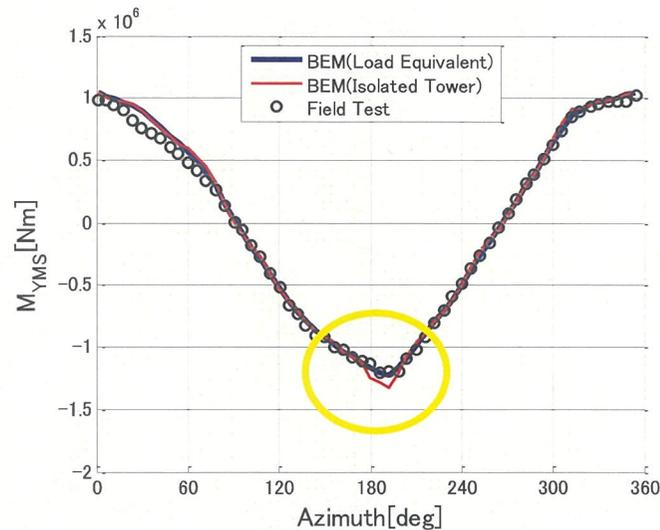


### 3.5 Load Equivalent Tower Shadow Model

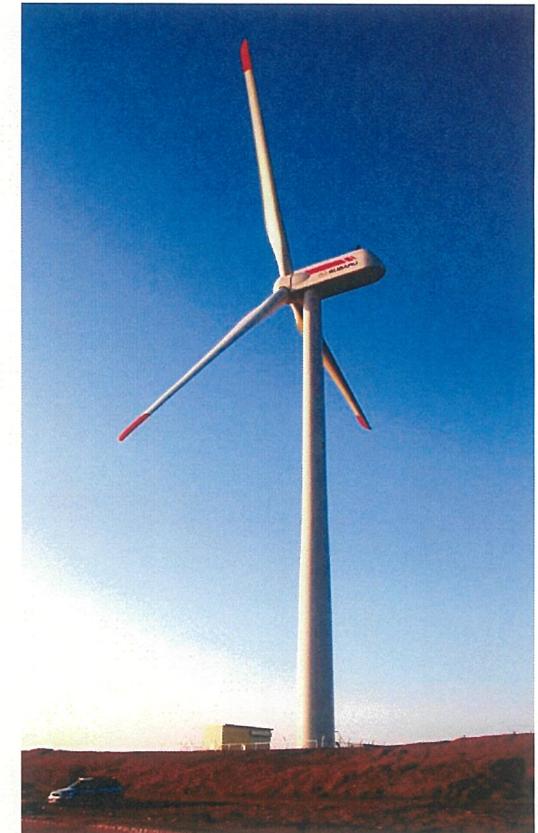
- Previous isolated tower model, which neglect the rotor-tower aerodynamic interaction, provides pessimistic tower shadow load fluctuation.
- The load equivalent tower shadow model, which considers the rotor-tower aerodynamic interaction to meet with CFD, was developed and was validated through field test of 2MW downwind turbine.
- The model was applied for the design of 2MW/80m ~ 5MW/127m downwind turbines.



Torque and Thrust at 13m/s (Rigid Model)



Main Shaft Bending to Azimuth (13m/s)



SUBARU80/2.0 Downwind Turbine

FY2006 Technology Award, JSES, 2007.  
Best Poster Award, Renewable Energy 2006.

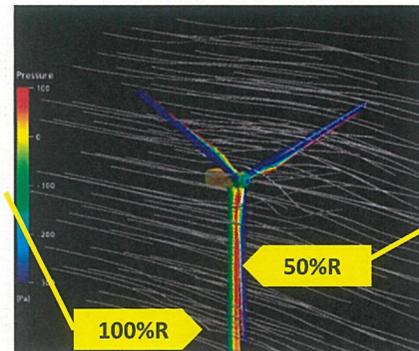
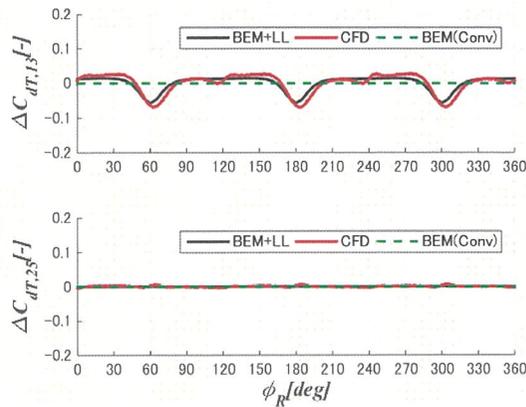
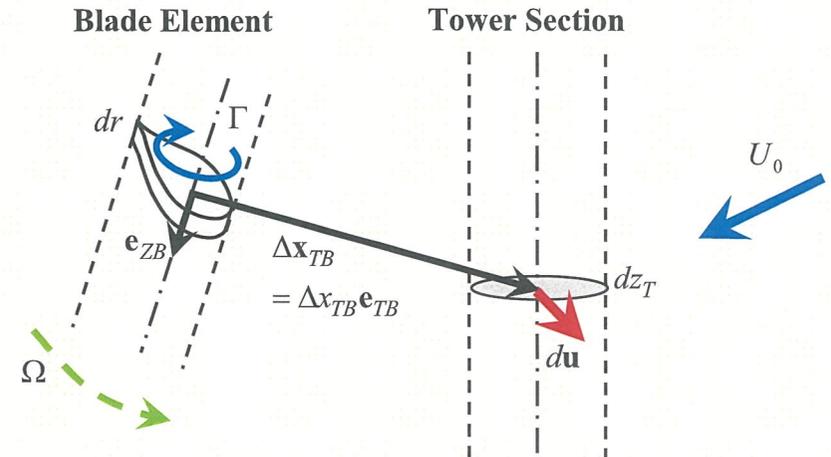
Yoshida, S., Load Equivalent Tower Shadow Modeling for Downwind Turbines, European Wind Energy Conference, 2007.

### 3.6 Tower Variable Load Model

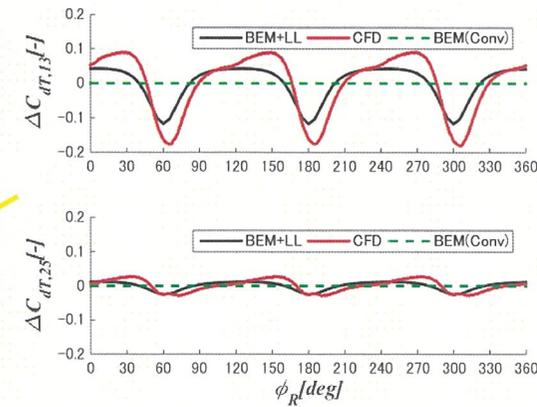
- The tower variable load by the circulation of the blades, which was neglected in the previous model (Conv.), was modelled by the lifting line model to consider the rotor-blade aerodynamic interaction.
- The model (BEM+LL) was verified by CFD.

Yoshida, S., Combined Blade-Element Momentum - Lifting Line Model for Variable Loads on Downwind Turbine Towers, energies, 2018.

$$u = \sum_{n=1}^B \left( \int_0^R \frac{\Gamma}{4\pi} \frac{\mathbf{e}_{BZ} \times \mathbf{e}_{TB}}{\Delta x_{TB}^2} dr \right)_n \quad \Delta C_{dT} = \frac{\pi D_T}{2U_0^2} \left( -U_0 \frac{du}{dx_T} + r\Omega \frac{dv}{dx_T} - w \frac{dw}{dx_T} \right)$$



Tower Load Variation (100%R and 50%R)



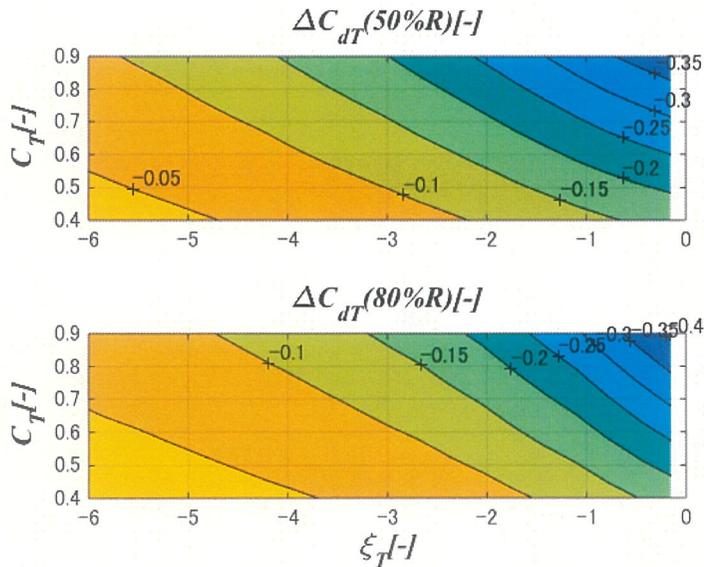
### 3.7 Tower Average Load Model

- The tower average load by the rotor thrust, which was neglected in the previous models (Former BEM), were modelled by the momentum theory.
- The model (Present) was validated by a wind tunnel test (Test).

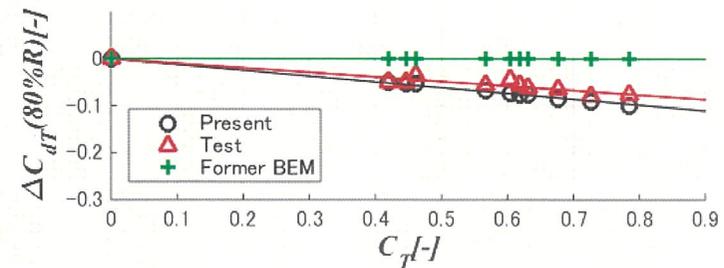
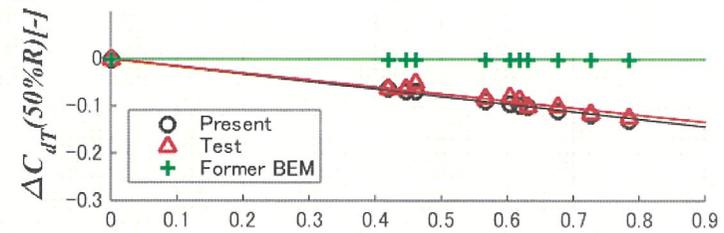
Yoshida, S., et al., Effect of Rotor Thrust on the Average Tower Drag of Downwind Turbines, *energies*, 12, 2, 227-241, 2019.01.

$$\Delta C_{dT} = \Delta C_{dT0} + \Delta C_{dTP}$$

$$= -C_{dT0} (1 - \mu_T^2) + \frac{\pi}{2} \mu_T \frac{d\mu_T}{d\xi_T}$$



$\Delta C_{dT}$  to  $C_t$  and Tower Relative Position  $\xi_T$



$C_{dT}$  Deviation to  $C_t(-4D_T)$

### 3.8 Dynamic Stall Model for Tower Shadow Effect

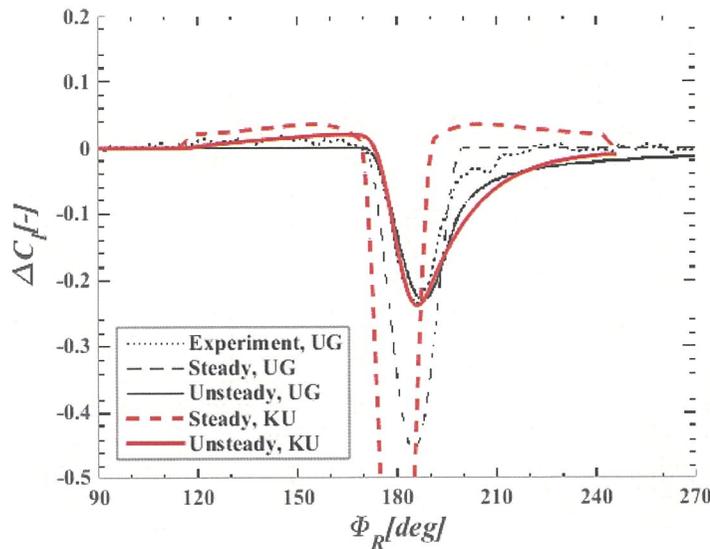
- The dynamic stall model for the tower shadow effect was modelled by thin airfoil theory.
- The model (Unsteady, KU) was validated by a wind tunnel test (Experiment).
- The influence was shown to be minor for large turbines.

Yoshida, S., Dynamic Stall Model for Tower Shadow Effects on Downwind Turbines and Its Scale Effects, *Energies* 2020, 13, 5237, 2020.10.

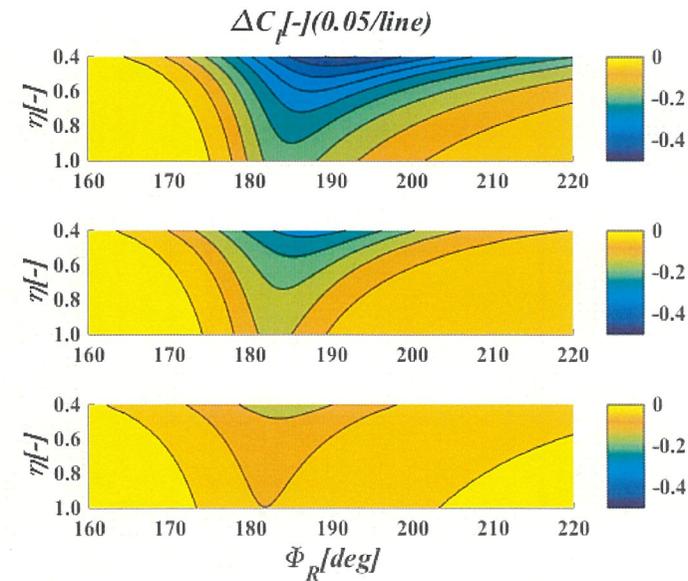
Munduate, X., et al., An Investigation of the Aerodynamic Responses of a Wind Turbine Blade to Tower Shadow, *J. Solar Energy Engineering*, 126, 2004, 1034-1040.

$$C_l = \frac{2\pi w_{ge}(s)}{W} \quad w_{ge}(s) = w_g(s) - X(s) - Y(s)$$

$$\begin{cases} X(s) = A_1 \int_0^s \frac{dw_g}{ds} \exp[-b_1(s-\sigma)] d\sigma \\ Y(s) = A_2 \int_0^s \frac{dw_g}{ds} \exp[-b_2(s-\sigma)] d\sigma \end{cases}$$



Validation with the Wind Tunnel Test



Deviation of Lift Coefficient: (T) x1, (M) x3, (B) x10



## 4. Researches on Floating Offshore Wind Turbine Technologies

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# 4.1 Demonstration Projects of FOWTs

## ①Hywind:

6MW × 5, commercial operation since 2017.



Statoil HP

## ②WindFloat®:

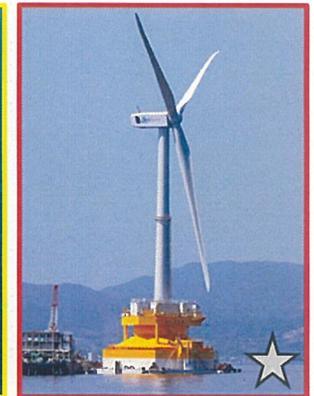
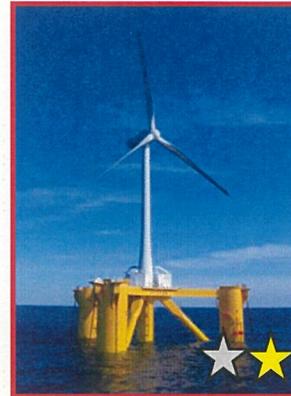
Demonstration completed in 2016.



WindFloat HP

## ④METI:

Demonstration of 2MW, 5MW 7MW FOWTs completed off the coast of Fukushima.



Fukushima Forward HP

## ⑤FLOATGEN, NEDO:

Under demonstration in France and Kitakyushu



IDEOL HP



NEDO HP

## ③MOE:

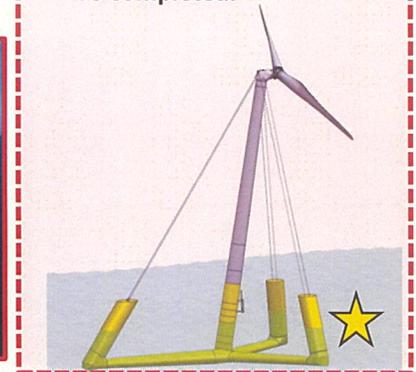
Commercial operation since 2017.



Toda Corp.

## ⑥NEDO OPTIFLOW:

FS completed.



★: Project member

☆: Committee member

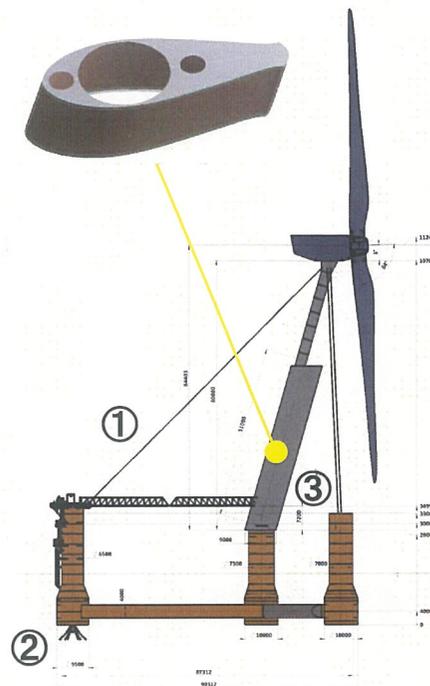
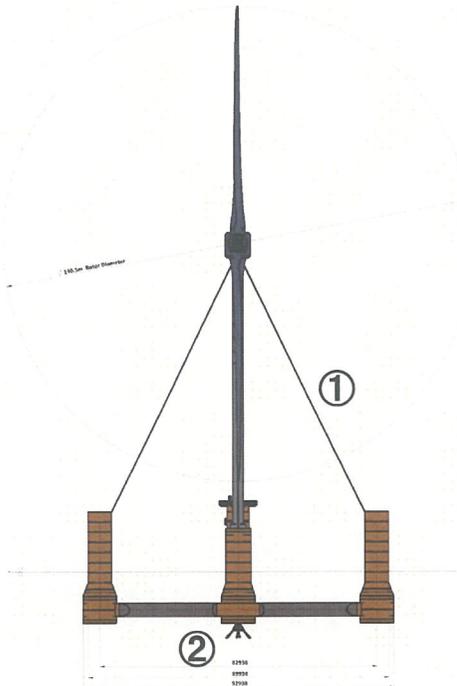
## 4.2 NEDO OPTIFLOW Outlines

### Features

- ① Guy wire: Tower enforcement and stiffening.
- ② Turret & single point mooring: Passive yaw.
- ③ Airfoil shaped inclined tower: Yaw stability.
- ④ Downwind rotor: Yaw stability.

### Problems

- 1) Yawing by current in power production (←②③)
- 2) Turret structure (←②)
- 3) Guywire strength/fatigue (←①)
- 4) Floater-tower coupling (←①③)



### Wind Turbine

- Type: 2B6
- Manufacturer: 2B Energy
- Number of blades: 2
- Rotor position: Downwind
- Rotor diameter: 140m
- Rated power: 6MW

### Floater

- Type: Single-point moored, semisubmersible
- Length: 81m
- Width: 81m

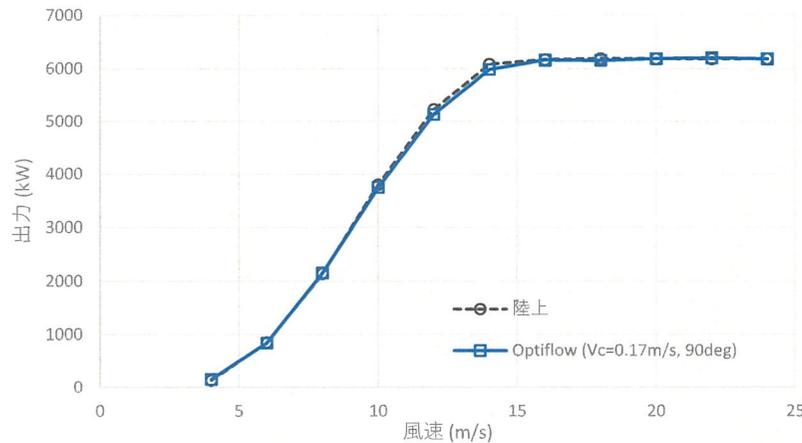
## 4.3 Passive Yaw Effects on Power Production

### Conditions

- Site: Kitakyushu (0.17m/s of current from 90deg).

### Power Curves

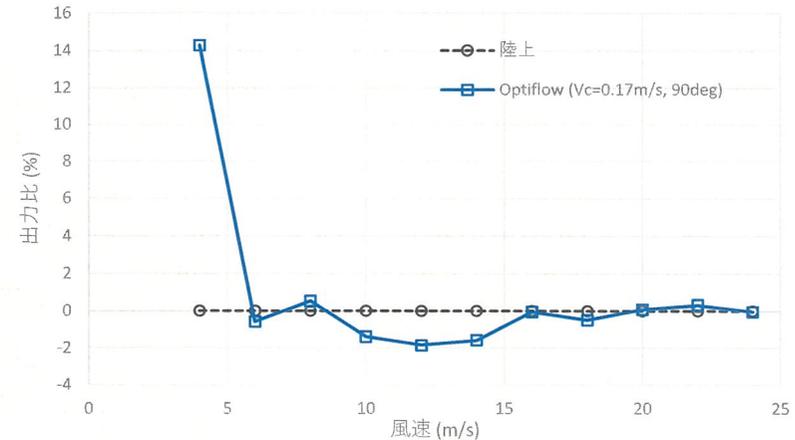
- Power of OPTIFLOW is 1.4~1.9% lower than that of onshore, in 9~15m/s of wind speed.



(a) Power curves

### Energy Production

- AEP of OPTIFLOW is slightly (-0.8%) decreased from onshore turbine in 7.5~10m/s of annual average wind speed.
- Differences in availability and frequency occurrence of current are not considered here.



(b) Relative power

(c) Annual energy production

Av. wind speed (m/s)	Annual Energy Production(MWh/yr)			Relative Energy Production(+/-%)		
	7.5	8.5	10.0	7.5	8.5	10.0
Onshore	2060	2535	3132	0.00	0.00	0.00
<b>OPTIFLOW</b>	<b>2044</b>	<b>2513</b>	<b>3106</b>	<b>-0.77</b>	<b>-0.84</b>	<b>-0.84</b>

## 4.4 Vortex Induced Vibration (1/2): Experiment Outlines

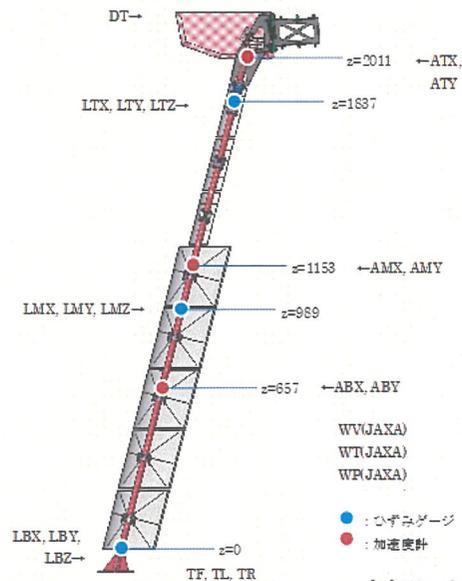
### Outlines

- The guy wire supported airfoil shaped inclined tower has complex structure in concerned the aeroelastic instability and vortex induced vibration. Wind tunnel test with 1/40 scale structural similar model was conducted for the confirmation.

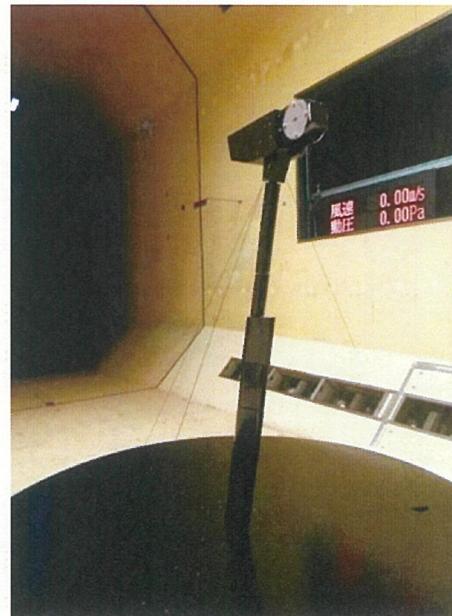
### Test Condition

- Wind tunnel: JAXA Low Speed Tunnel
- Wind speed: 8m/s (51.2m/s for full scale), 1~12m/s
- Yaw angle: 0~180deg
- Blade: without/with (horizontal)
- Blade pitch: Influences of floater inclination and pitch failure

### Measurement



(a) Strain, acceleration sensor positions



(b) Model installed in the wind tunnel  
L) No blade  
R) Blades at horizontal

## 4.5 Vortex Induced Vibration (2/2): Evaluation

### Outlines

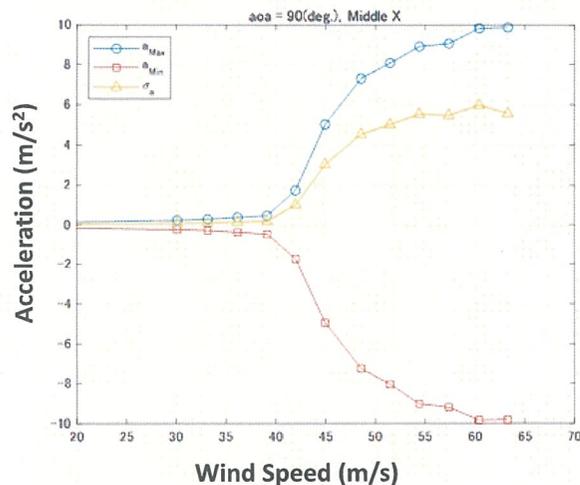
- The airfoil shaped tower generates strong vortex induced vibration. And the guy wires affects the vibration.
- The strength and fatigue were evaluated by the wind tunnel test, FEM, 2D CFD.

### Strength and Fatigue Results

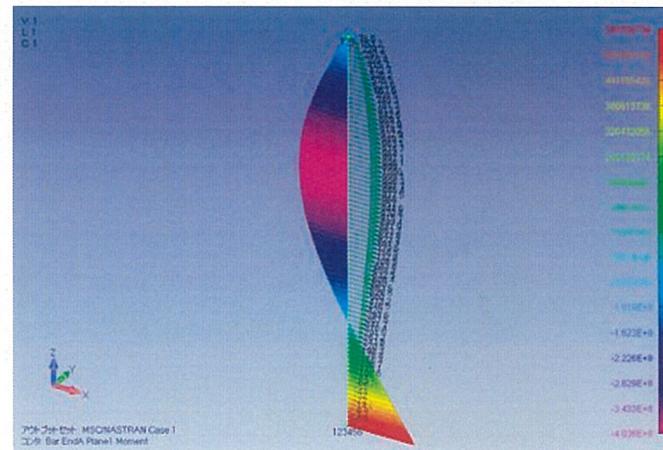
- Max. effort (load/strength): 21%
- Fatigue damage (10min assumed): 1.4%

### Analysis Method

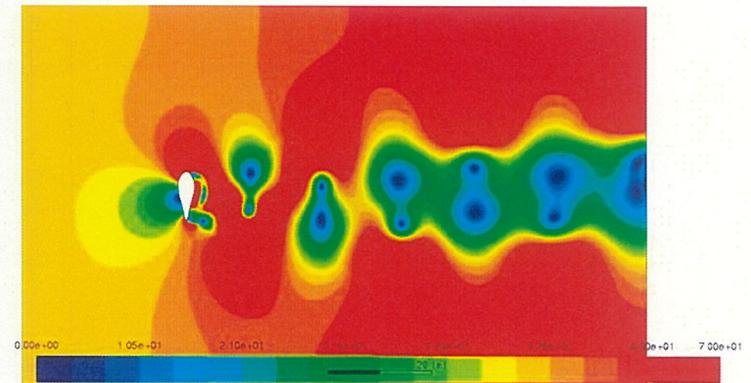
- 1) Bending moment distribution by FEM.
- 2) Calculate the acceleration to AOA by the 2D CFD and the aero-elastic wind tunnel test results.
- 3) Calculate maximum bending moment at tower base, caused by the vortex induced vibration.
- 4) Furthermore, strength and fatigue are evaluated (S355 Steel, Butt weld).



(a) X-wise vibration (full scale): Tower center



(b) FEM result for 1kN/m distributed load  
(Max 562kNm @base)



(c) Wind speed distribution by CFD: AOA=90deg

## 4.6 Quasi-steady Stability Analysis

### Simulation Results

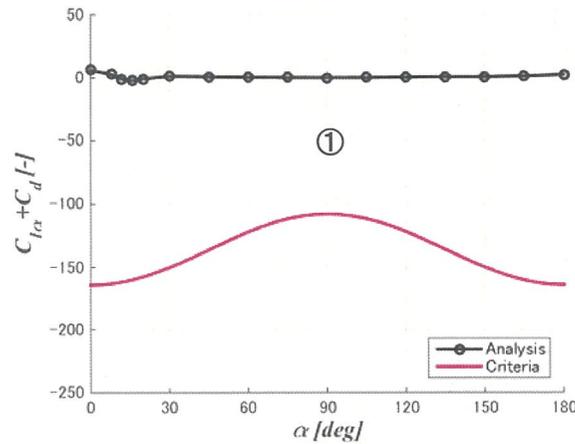
- A quasi-steady stability analysis code was developed for the guy wire supported airfoil shaped inclined tower.

#### (1) Basic characteristics ( $C_{l\alpha}$ , $C_d$ , $\alpha$ : yaw angle)

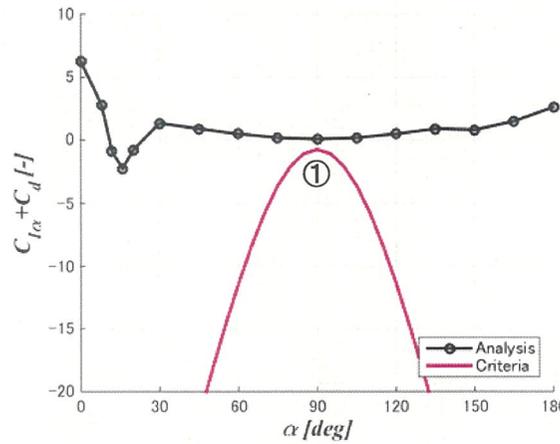
- 1st (a) and 2nd (b) modes are stable enough (Analysis > Criteria). → ①

#### (2) Influence of blades

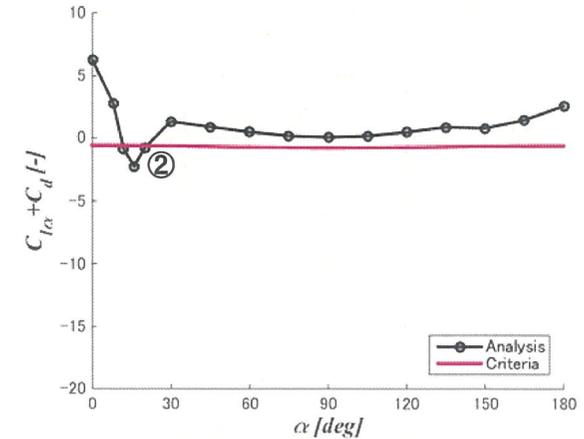
- 2nd mode with no blade (c) shows instability around 15deg, where lift curve slope is negative. → ②
- 0.0055/deg (5% of nominal) of small lift slope is enough to stabilize. → ③



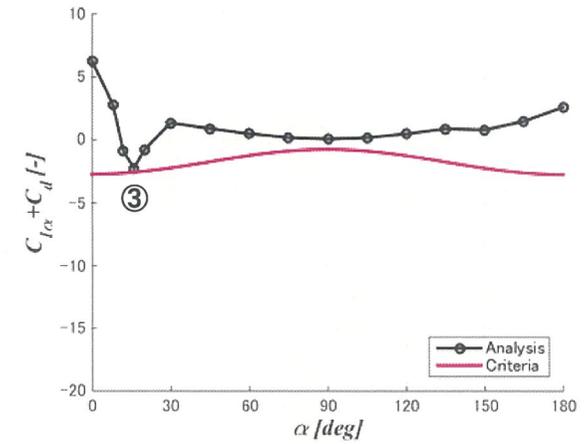
(a) 1st mode



(b) 2nd mode



(c) 2nd mode: no blade



(d) 2nd mode: 0.0055/deg of lift curve slope

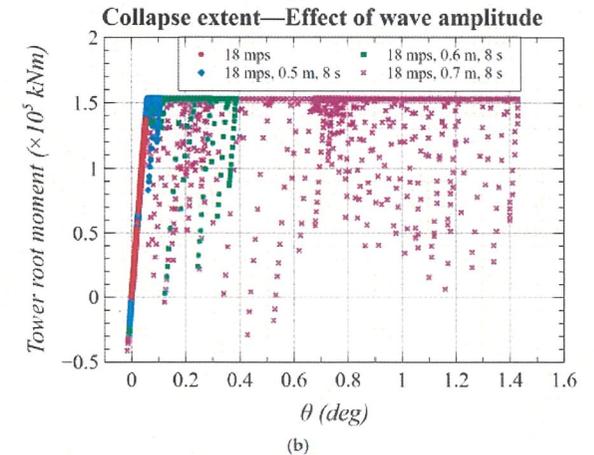
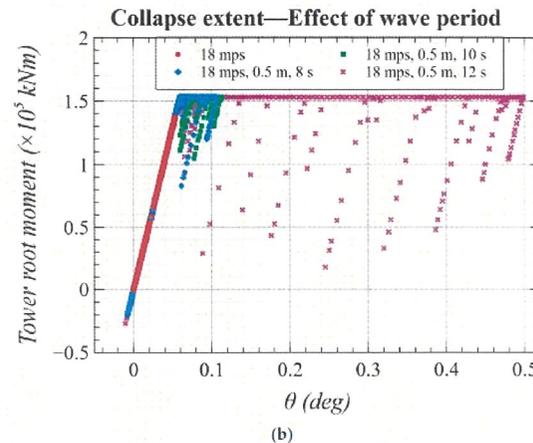
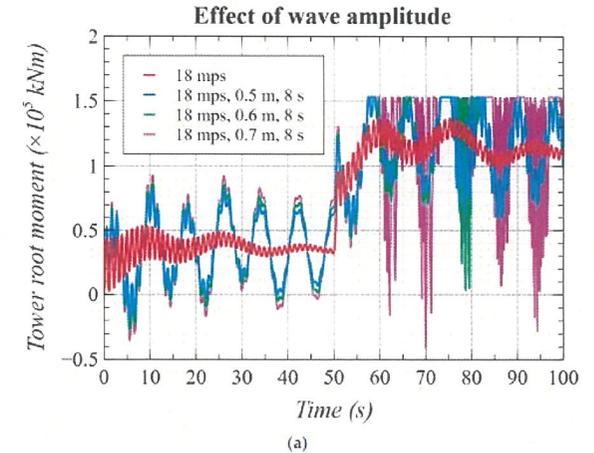
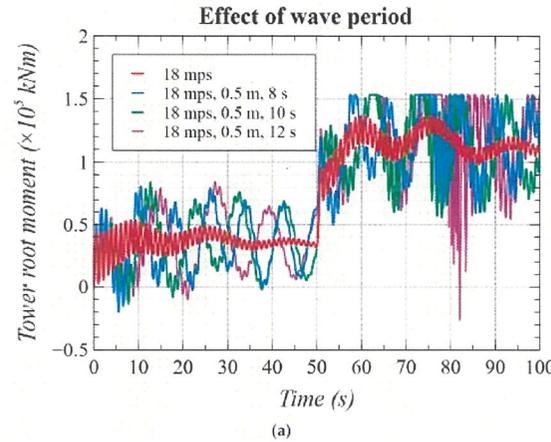
# 4.7 Collapse Behavior

## Outlines

- The collapse behavior mechanisms of onshore and spar-FOWTs under blade pitch malfunction were investigated. The collapse extent, which is a quantitative measure of the damage in the plastic region at the collapsing section, was evaluated and the moment–rotational angle relationships are discussed.

## Results

- This shows that a spar-FOWT is 8 times more critical than the onshore case for failures.
- Regarding the collapse behavior of the spar-FOWT, the collapse extent increases with increasing wave periods and amplitudes under the same wind conditions.



Srinivasamurthy S., Pandit A., Yoshida S., Collapse Behavior of Onshore and Spar-Floating Wind Turbine Towers During Blade Pitch Malfunction, Journal of Marine Science and Engineering, 2026.

Spar FOWT collapse: (T) Tower base bending, (B) collapse extent.



## 5. Researches on Data Science

1. Division of Offshore Wind Energy System
2. Researches on Optimization Methods
3. Researches on Downwind Turbine Technologies
4. Researches on Floating Offshore Wind Turbine Technologies
5. Researches on Data Science
6. Conclusion

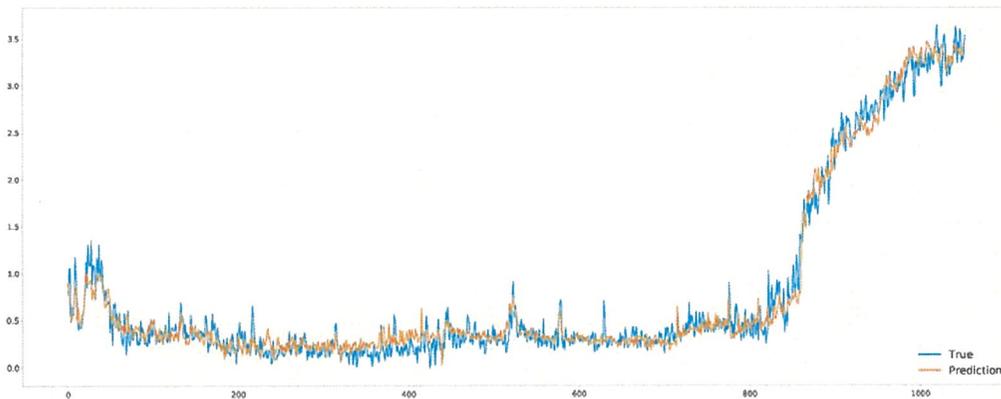
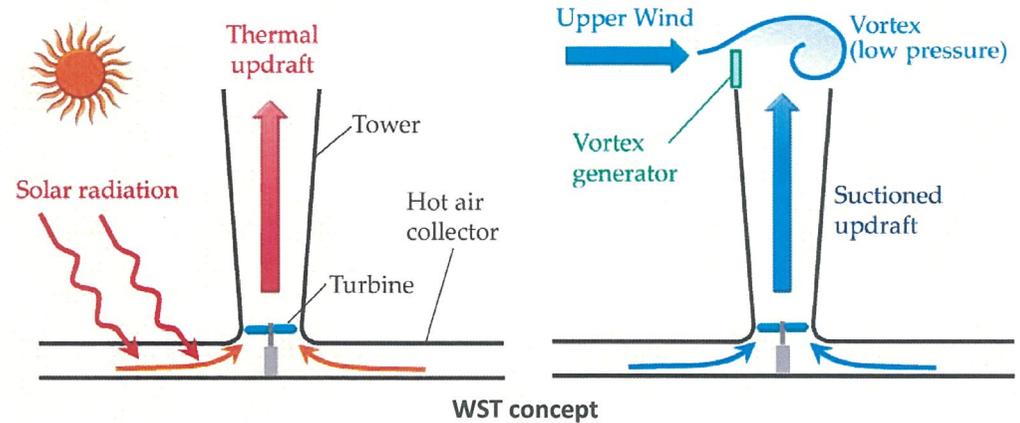
# 5.1 Wind Solar Tower

## Outlines

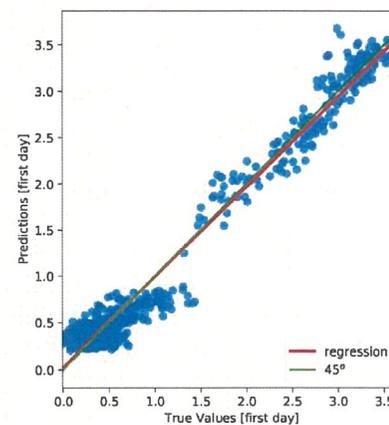
- Energy prediction by Machine Learning/Deep Learning.

## Results

- Prediction of up flow wind speed of WST by Machine Learning.
- Prediction of energy production by Deep Learning.



Time series of up-draft wind speed true and prediction



True vs prediction

Rushdi M.A., Yoshida S., Watanabe K., Ohya Y., Machine learning approaches for thermal updraft prediction in wind solar tower systems, Renewable Energy 177 (2021) 1001-1013.

## 5.2 Load Estimation by Machine Learning (ML)

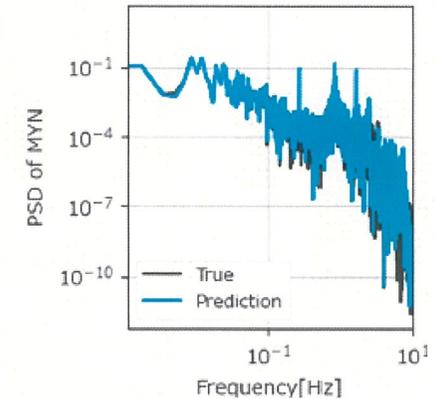
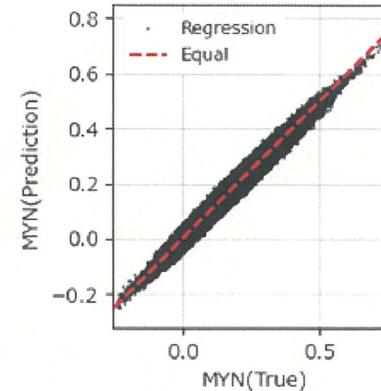
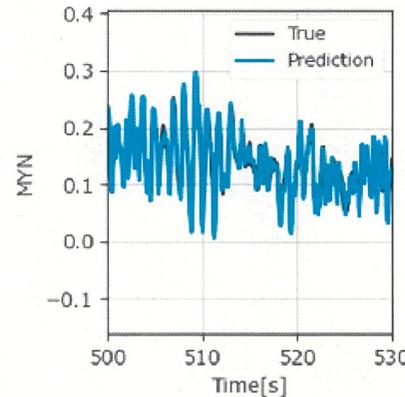
### Outlines

- A method for predicting the time history of hub center loads was developed by combining simple measurement and ML.
- Application: prediction of failures, individual pitch control (IPC).

### Results

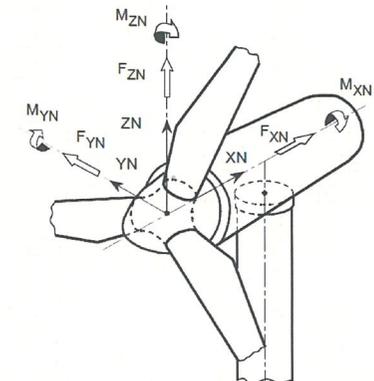
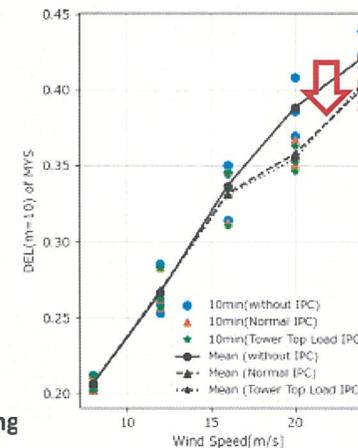
- MXN, MYN, MZN: linear ML, tower top loads.
- FXN: nonlinear ML, operating conditions, nacelle accelerations, tower top loads, and tower bottom loads.
- MYN, MZN: linear ML, tower top loads, operating conditions, →DEL ( $m = 10$ ) errors were 10% for MYN and 23% for MZN.
- IPC using MYN & MZN: shown to be effective to reduce the fatigue loads blade root flapwise bending.

Kiyoki S., Yoshida S., Rushdi M.A., Estimation of Hub Center Loads for Individual, Pitch Control for Wind Turbines Based on Tower Loads and Machine Learning, electronics, 2024.



Linear Regression, with tower, pitch angle, generator speed, tower top MX, MY, and MZ: (L) time series, (C) correction, (R) power spectrum.

Effects of IPC Using ML Estimated Data: Damage Equivalent Load ( $m=10$ ) Blade Root Flapwise Bending

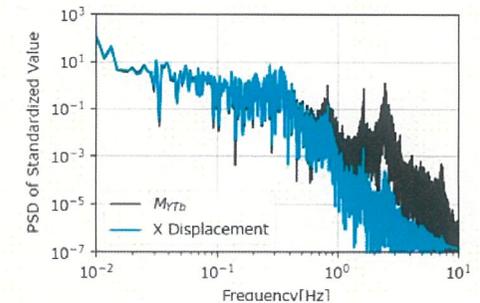
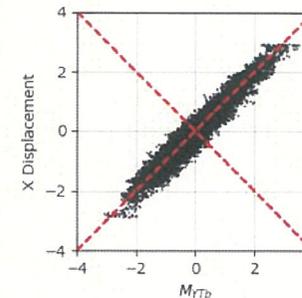
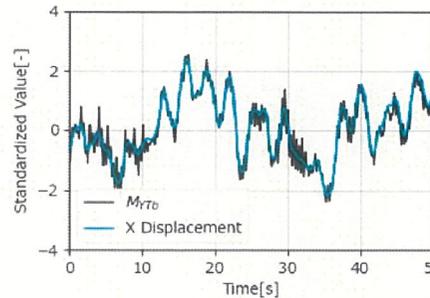


XN in direction of the rotor axis  
 ZN upwards perpendicular to XN  
 YN horizontally sideways, so that XN, YN, ZN rotate clockwise

## 5.3 Tower Load Prediction by Machine Learning (ML)

### Outlines

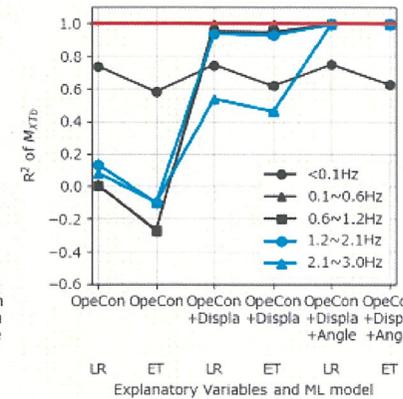
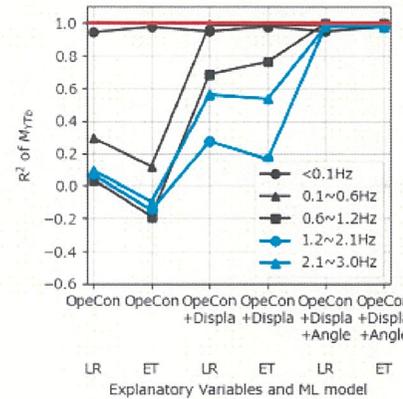
- A method for predicting WT tower loads was developed based on ML and simplified measurements of the nacelle behavior.
- Application: load estimation for the foundations under the soil and floaters.



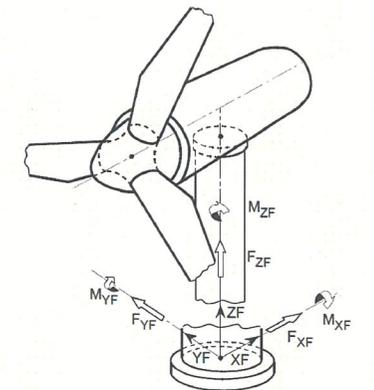
Correlation between MYTb and nacelle X displacement at 14 m/s

### Results

- MYF, MXF are highly correlated with the nacelle displacement and angle in the low- and high-frequency components, respectively.
- The prediction accuracy of the low-frequency components of MYF was increased using operating condition data with nonlinear ML.
- The fatigue and extreme loads of MYF and MXF can be predicted using operating condition and nacelle acceleration data. In addition, the prediction accuracy of high-frequency components increases when including nacelle angle velocity.



R2 or prediction models for each frequency



XF horizontal  
ZF vertically upwards in direction of the tower axis  
YF horizontally sideways, so that XF, YF, ZF rotate clockwise



## 6. Conclusion

1. Division of Offshore Wind Energy System
2. Researches on Optimization Methods
3. Researches on Downwind Turbine Technologies
4. Researches on Floating Offshore Wind Turbine Technologies
5. Researches on Data Science
6. Conclusion



## 6.1 Conclusion

- Outlines of the following researches at IOES-OWES were introduced.
- Optimization of wind turbine is important for application of new technologies and the development of large wind turbines, as well as the development of element or component technologies.
- Downwind turbine technologies are promising for future super large floating offshore wind turbines. 4 models were developed for the tower shadow model for load calculation.
- Technologies on advanced floating offshore wind turbine technologies, such as performance of the single point passive yawing, stability analysis, vortex induced vibration, and collapse behavior.
- Applications of ML to load estimation were developed.

**Thank you!**

**International Joint Usage / Joint Research Promotion Workshop  
2026/03/09 @Saga University**

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