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Japanese-Danish Joint Workshop
Future Green Technology

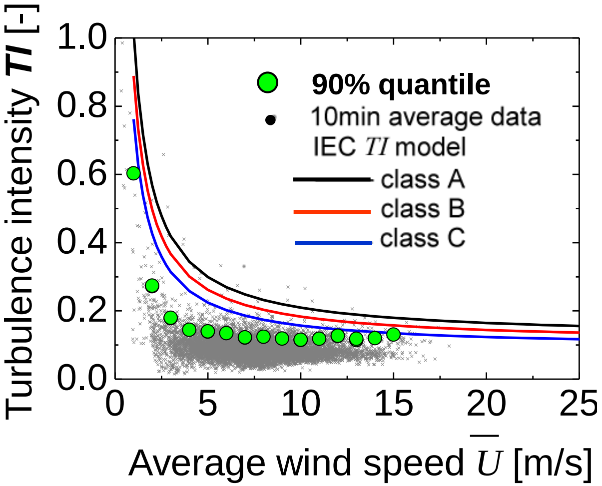
Effects of Inflow Wind Condition and Structural Oscillation on Blade Loads of HAWT Rotor

Yutaka HASEGAWA
Nagoya Institute of Technology

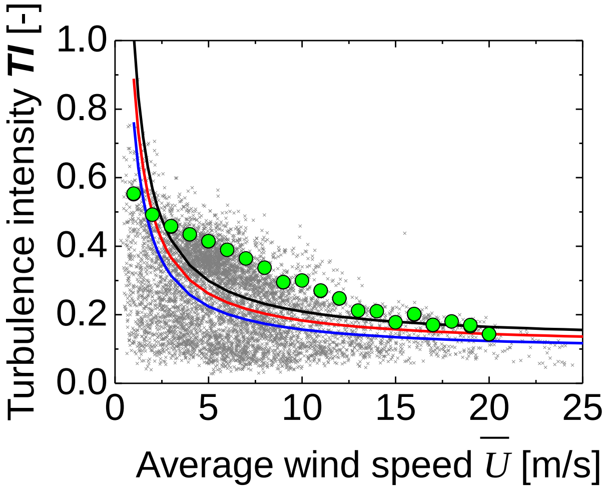
CONTENTS

Background 1/2

- **Many turbines installed in mountainous area, in Japan:**
  - High turbulence intensity over the complex terrain.
  - **Special attention should be paid to effects of inflow condition on fatigue load.**



measured at **50 m** elevation



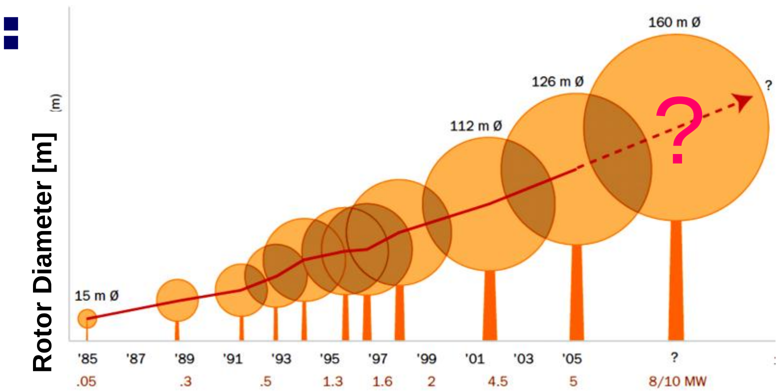
measured at **40 m** elevation

Background 2/2

- **Increasing size of wind turbines:**

⇒ **Decrease in eigen freq.**
of blade oscillation
- *close to rotational freq. for large rotors*
- *possible resonant oscillation of blade*

⇒ **Increase in non-uniformity of inflow**
into rotor plane,
leads to increased effects from **inflow condition**



<u>**Increase in Rotor Diameter**</u>

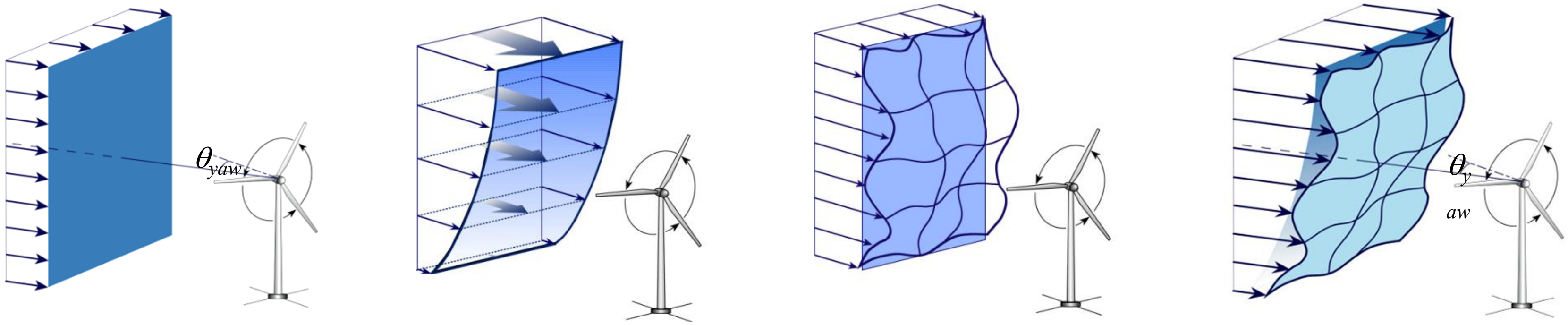
In order to design large wind turbines

Effects of <u>**inflow condition**</u> and <u>**blade oscillation**</u> on the **blade loads** have to be predicted in design process.

<u>**Large Wind Turbine**</u>
(D = 126m, P = 5MW)

Objectives

- **Objective Ⅰ :** Clarify **effects of inflow condition** on blade loads by **simple numerical analysis**



Yaw misalignment　　Sheared inflow　　Turbulent inflow　　Combined inflow

- **Objective Ⅱ :** Clarify **effects of blade oscillation** on blade loads by **fluid-oscillation coupled analysis**

Aerodynamic Analysis
Flow Field around Rotor
（Panel Method）

Aerodynamic Load →

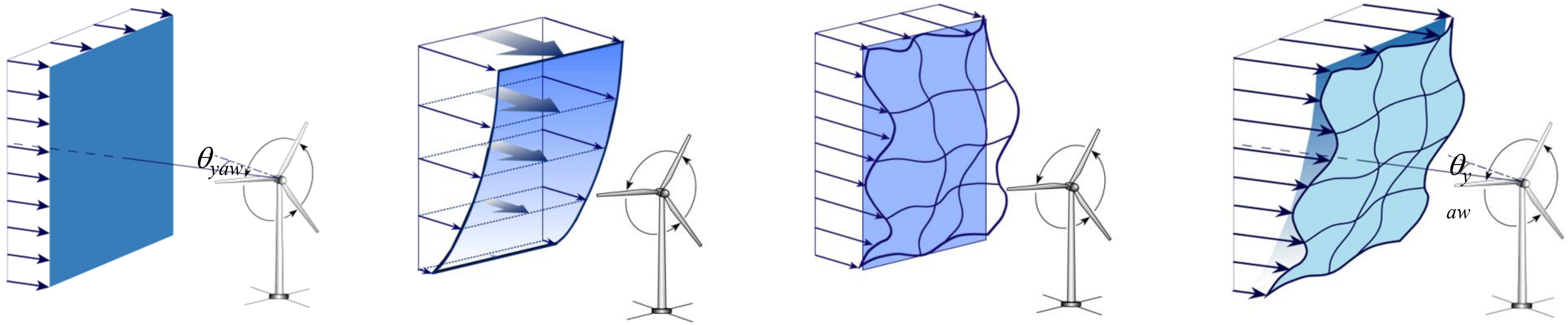
← Displacement & Velocity of Blade Oscillation

Oscillation Analysis
Blade Oscillation
（Multi-Body Dynamics）

Two-way coupled analysis model

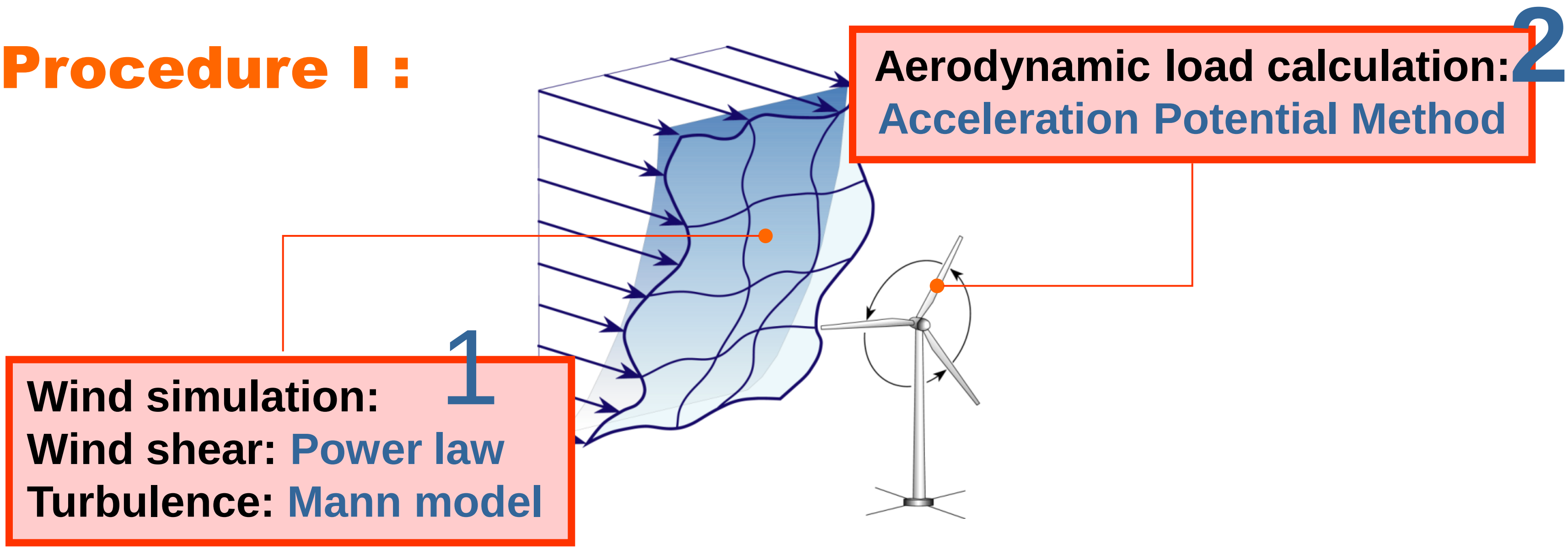
Objective I and Procedure I

Objective I : Clarify **effects of inflow condition** on blade loads by **simple numerical analysis**



Yaw misalignment | Sheared inflow | Turbulent inflow | Combined inflow

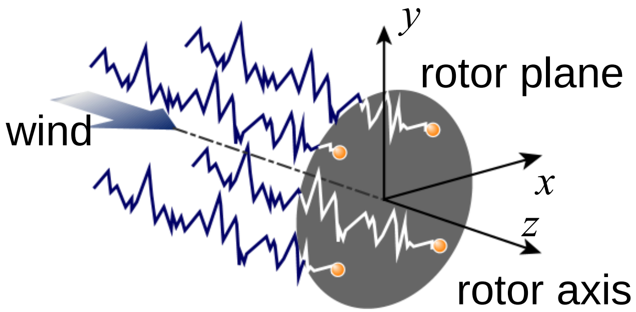
Procedure I :



Wind Simulation

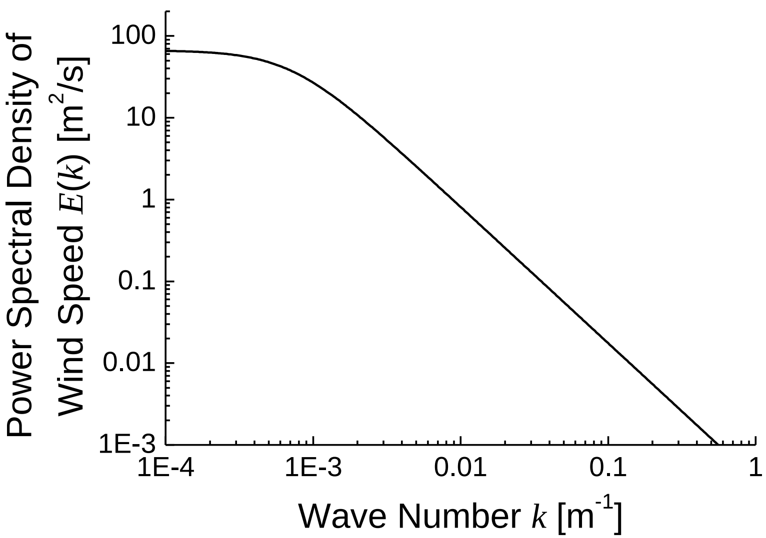
■ Simulation of turbulence by Mann Model

- Generates turbulent wind time series at multiple points on rotor plane
- Takes account of spatial correlation between time series
- Power Spectrum：
  von Karman Spectrum（isotropic turbulence）

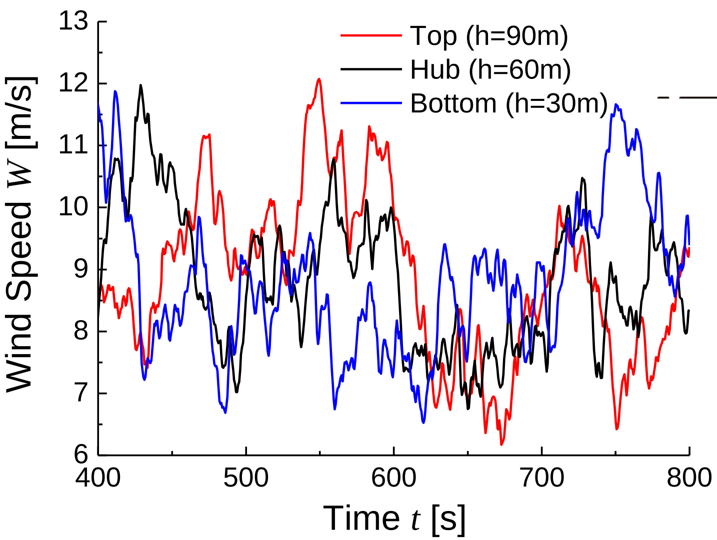


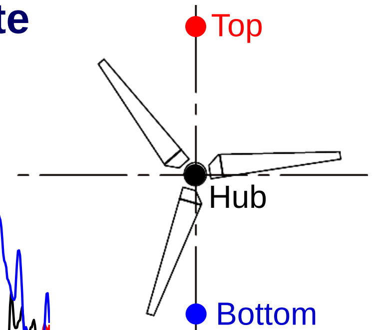
$$E(k)=\alpha_K \varepsilon^{2/3} L^{5/3} \frac{L^4 k^4}{\left(1+L^2 k^2\right)^{17/6}}$$

L ：turbulent length scale
α_K ：Kolmogorov constant
ε ：viscous dissipation rate



von Karman Spectrum





Example of turbulent inflow by Mann model

Acceleration Potential Method

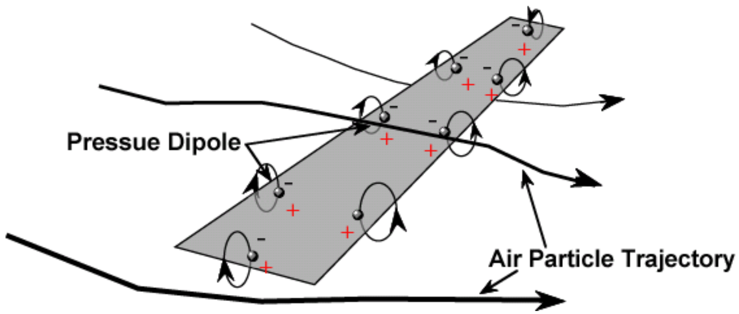
- Assume inviscid and incompressible flow
- Laplace equation for pressure perturbation

Euler eq. $$\frac{\partial \mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}=-\frac{1}{\rho}\nabla p$$

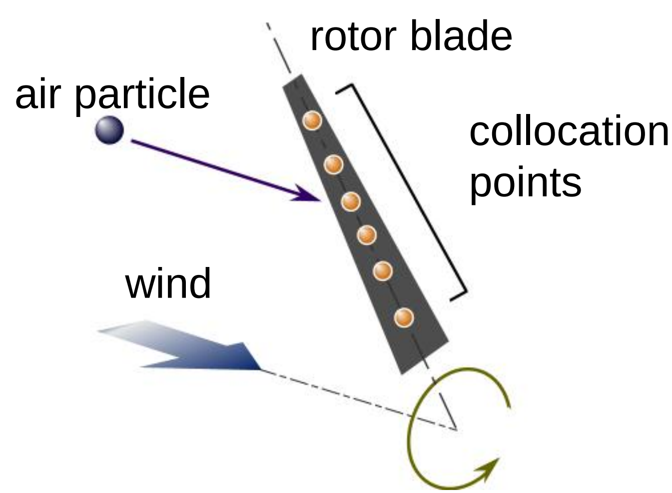
linearized

Laplace eq. $$\nabla^2 p=\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}+\frac{\partial^2 p}{\partial z^2}=0$$

- Representation of rotor blades by spanwise and chordwise pressure distributions
- **Ability to handle three dimensional unsteady flow without using empirical constants unlike BEM**



Rotor blade represented by pressure



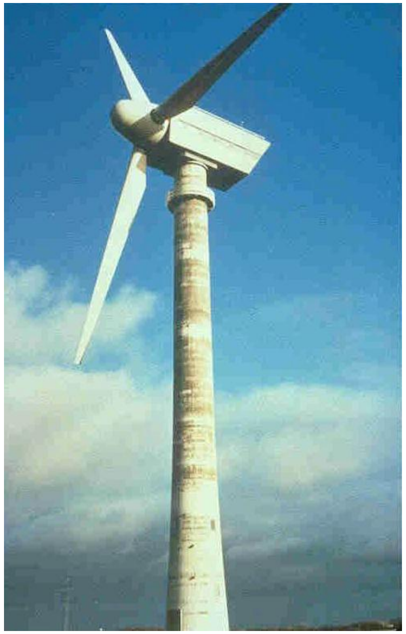
Collocation points on blade

Calculation Condition I

Rotor configuration I :

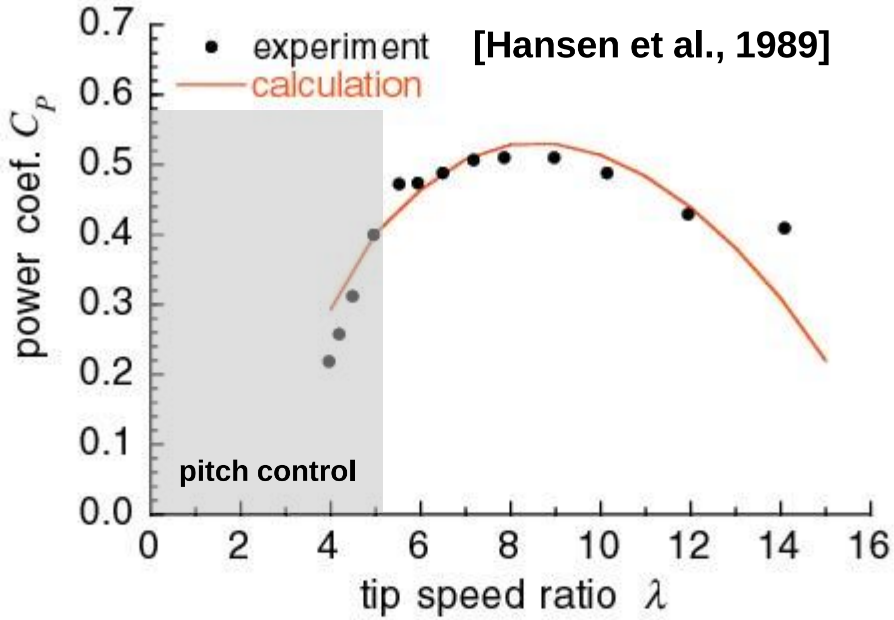
- **Tjæreborg Turbine (Denmark)**

number of blades	3	rotor diameter	61 [m]
rotational speed	22 [rpm]	rated power output	2 [MW]



Tjæreborg Turbine

Validity of calculation method



Rotor performance

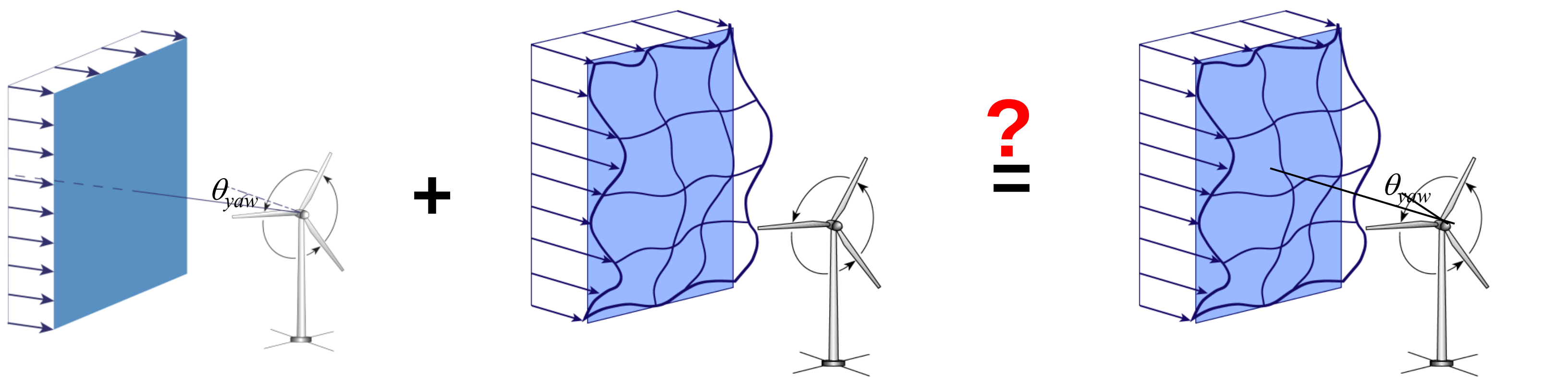
Power Coefficient: $C_P = \dfrac{P}{\rho W_{hub}^{3} \pi R^2 / 2}$

Tip Speed Ratio: $\lambda = \dfrac{\Omega R}{W_{hub}}$

ratio of the rotor tip speed
to the wind speed

■ Examples of inflow conditions

- Yawed inflow (uniform inflow with yaw misalignment)
- Turbulent inflow
- Yawed turbulent inflow (turbulent inflow with yaw misalignment)



Yawed inflow　Turbulent inflow　Yawed turbulent inflow

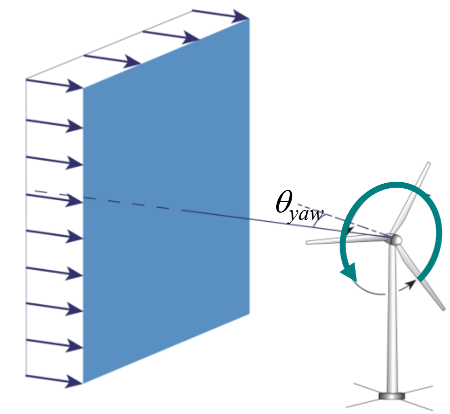
- Is summation of individual inflow effects on fatigue load equal to combined inflow effects??
- Yawed inflow effects are not considered in the fatigue load analysis in IEC standard.

Yawed Inflow 1/3

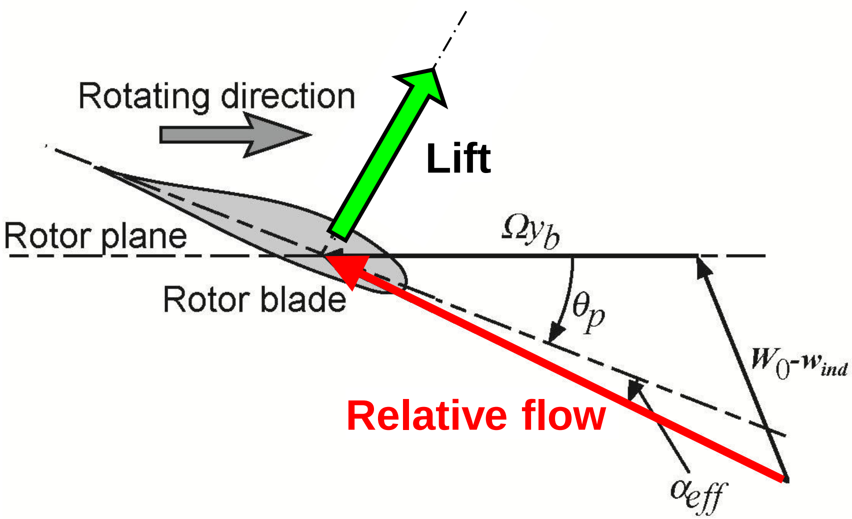
■ **Relative flow to the rotating blade section changes periodically**

In the rotor plane .....

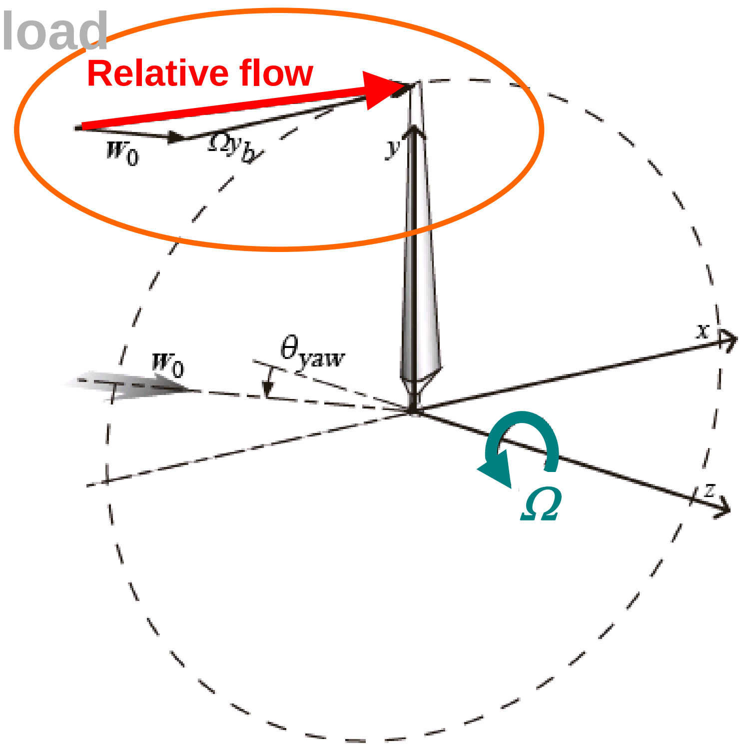
- **Upper half :**
  smaller attack angle → lower blade load
- **Lower half :**
  larger attack angle → higher blade load



Yawed uniform inflow

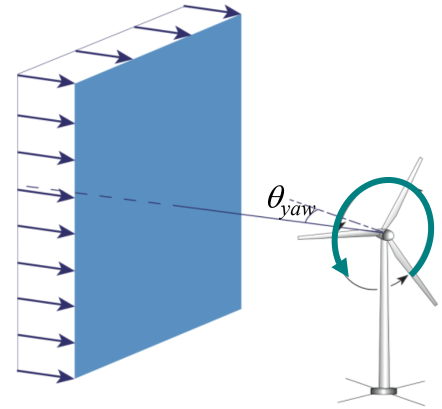


Relative flow to blade section
at the top of rotor plane



Yawed Inflow 2/3

■ **Relative flow to the rotating blade section changes periodically**



Yawed uniform inflow

In the rotor plane .....

- **Upper half :**
  smaller attack angle → lower blade load
- **Lower half :**
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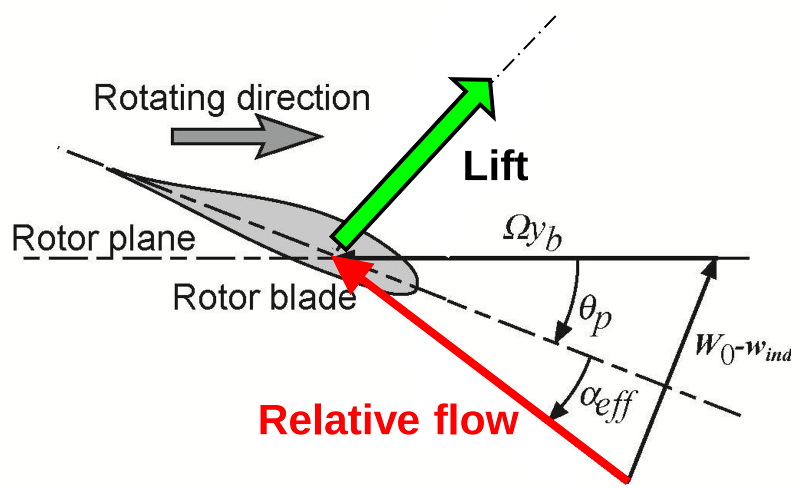
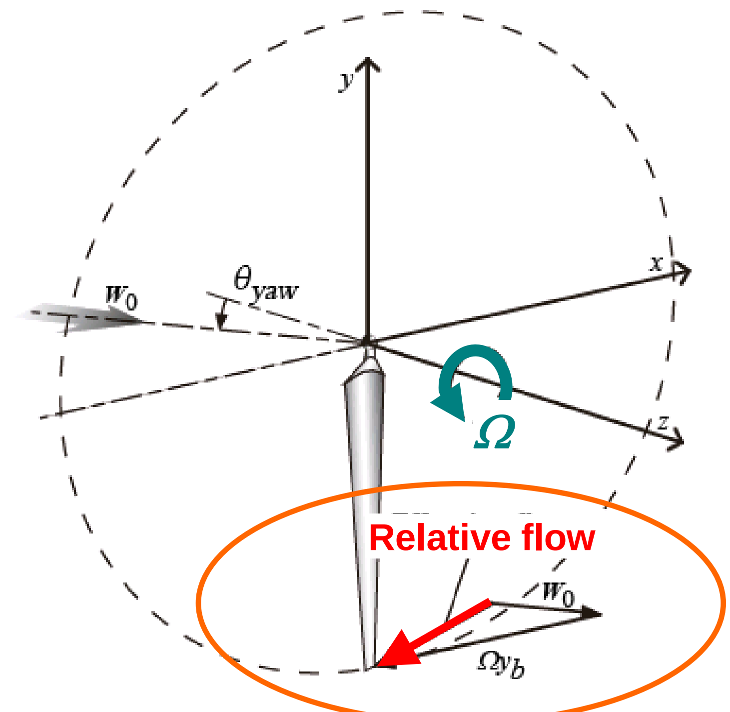


Relative flow to blade section
at the bottom of rotor plane

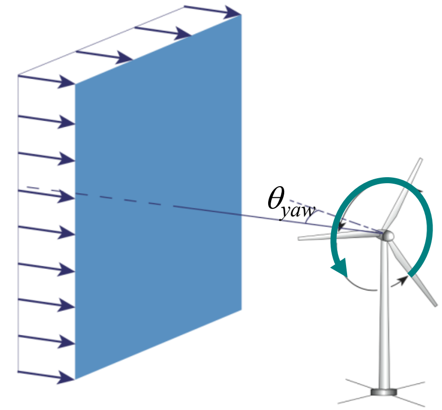


Yawed Inflow 3/3

■ **Relative flow to the rotating blade section changes periodically**

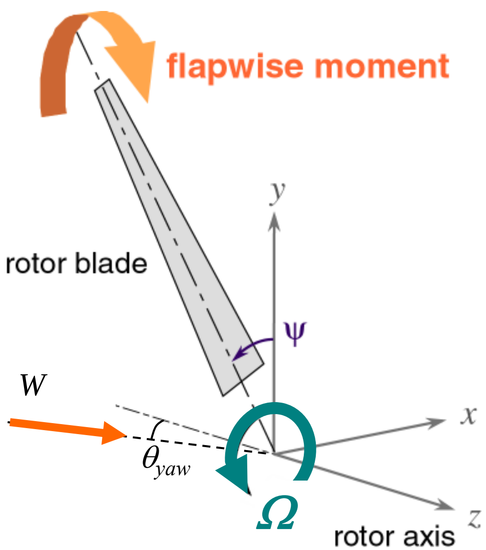
In the rotor plane .....

- **Upper half :**
  smaller attack angle → lower load
- **Lower half :**
  larger attack angle → higher load

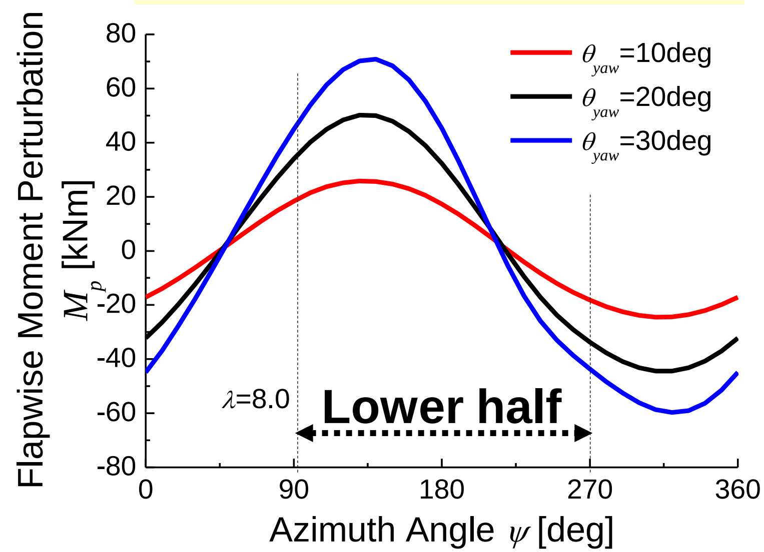


Yawed uniform inflow

Periodic fluctuation due to yaw misalignment



Definition of Flapwise Moment

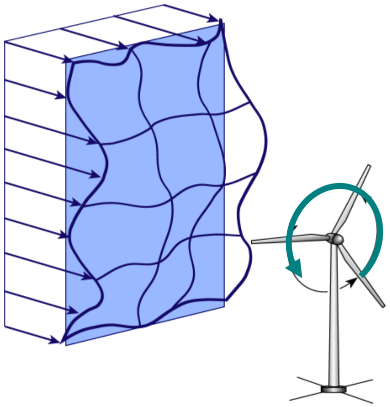


Flapwise moment fluctuation due to yaw misalignment at λ=8

Turbulent Inflow

■ Turbulent Inflow without Yaw Misalignment

- **Blade load due to turbulence**
  - Complex fluctuation of blade load
  - Amplitude of fluctuation increases with turbulence intensity ***TI***

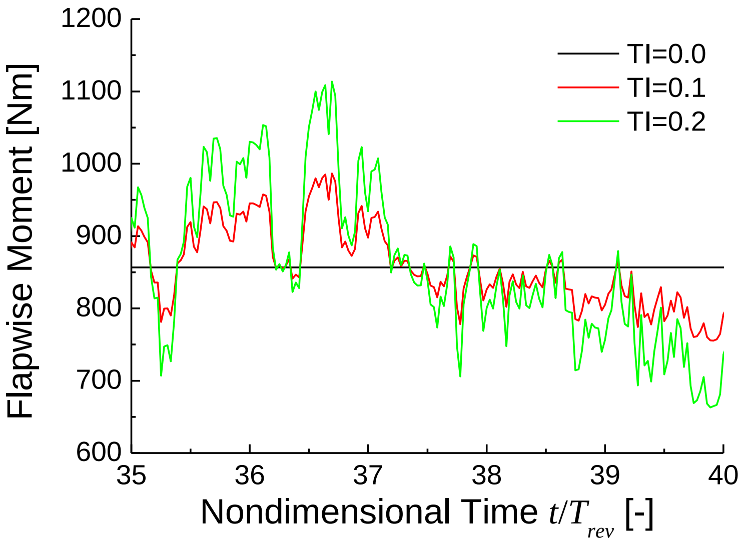


Turbulent inflow

Turbulence Intensity : $TI = \dfrac{\sigma}{W_{hub}}$

σ : **standard deviation of velocity fluctuation**

W_{hub} : **velocity at hub height**



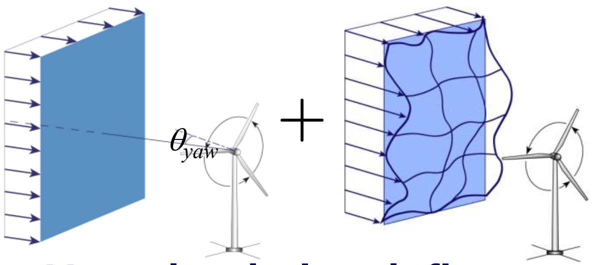
Flapwise moment fluctuation for various turbulence at λ=8

Yawed Turbulent Inflow 1/2

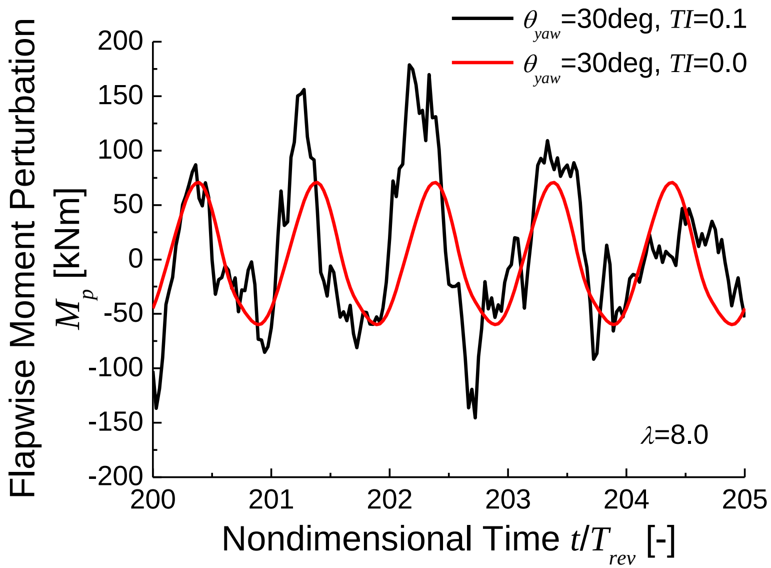
■ Turbulent Inflow with Yaw Misalignment

‣ Fatigue load on blade

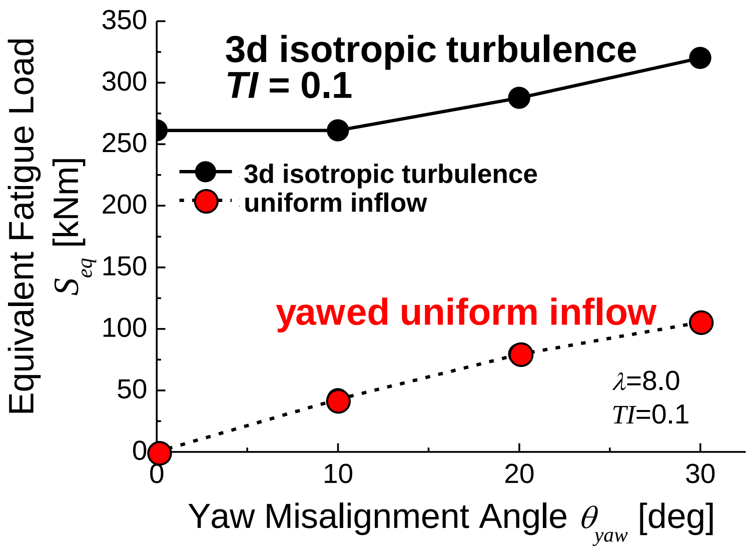
- Yawed uniform inflow condition
  → Linear increase with yaw misalignment angle
- Yawed turbulent inflow condition
  → Non-linear increase with yaw misalignment angle



Yawed turbulent inflow



Blade load fluctuation due to yawed inflow
with and without turbulence

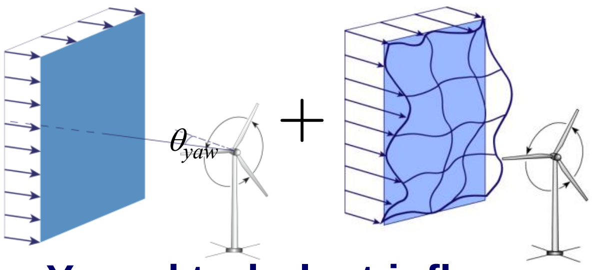


Effect of yawed turbulence
on **fatigue load on blade**

Yawed Turbulent Inflow 2/2

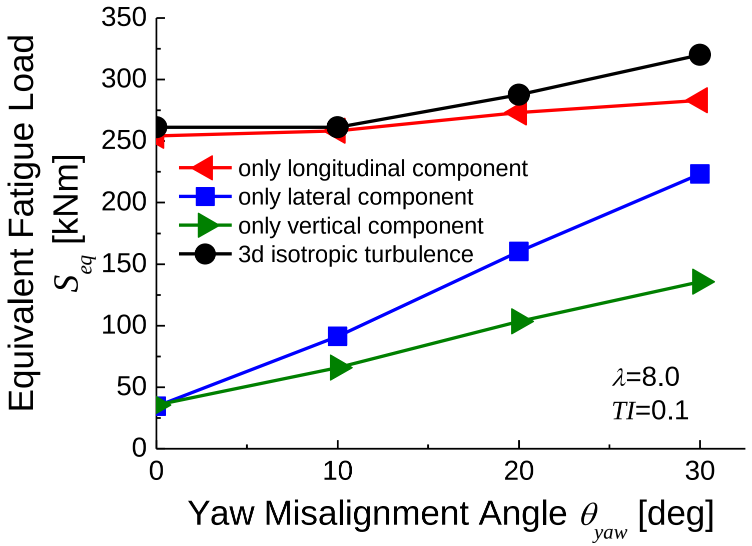
■ Turbulent Inflow with Yaw Misalignment

- Compare effects of turbulent components
  - ◀ longitudinal component
  - ■ lateral component
  - ▶ vertical component
  - ● 3d isotropic turbulence



Yawed turbulent inflow

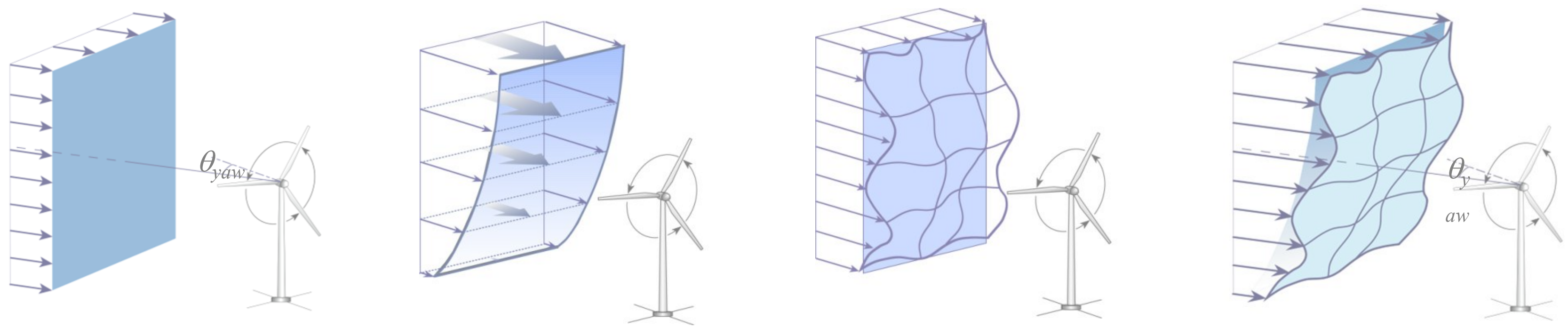
- **Normal Inflow (θ_{yaw}=0deg)**
  - **longitudinal comp. has dominant effect on Fatigue Load**
  - small effect from lateral and vertical comp.
- **Yawed Inflow**
  - **lateral comp. gives larger effects with yaw misalignment angle**



Effect of turbulence component and yaw misalignment on **fatigue load on blade**

Objectives II

- **Objective I :** Clarify the effects of **inflow condition** on blade loads by **simple analysis**



Yaw misalignment | Sheared inflow | Turbulent inflow | Combined inflow

- **Objective II :** Clarify the effects of **blade oscillation** on blade loads by **fluid-oscillation coupled analysis**

Aerodynamic Analysis

Flow Field around Rotor
(Panel Method)

Aerodynamic Load →

← Displacement & Velocity of Blade Oscillation

Oscillation Analysis

Blade Oscillation
(Multi-Body Dynamics)

Two-way coupled analysis model

Calculation Condition II

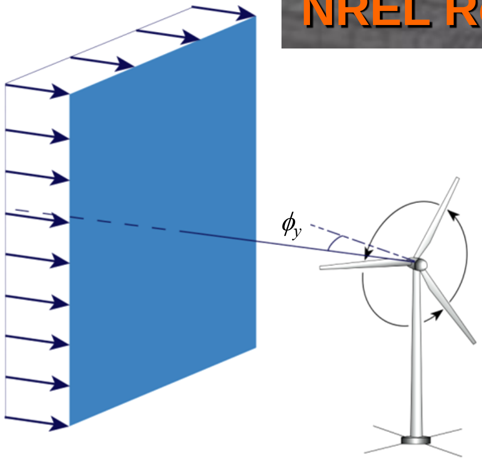
Reference Data : Wind tunnel experiment conducted by NREL (National Renewable Energy Laboratory)

■ Configuration of NREL Rotor

Blade num.	**2**	Rotational speed	72 [rpm]
Rotor diameter	**10 [m]**	Wing section	NREL S809

■ Calculation Condition

Uniform inflow	**without turbulence**
Yaw Misalignment	**0～30 [deg]**
Wind Speed	5～12 [m/s]

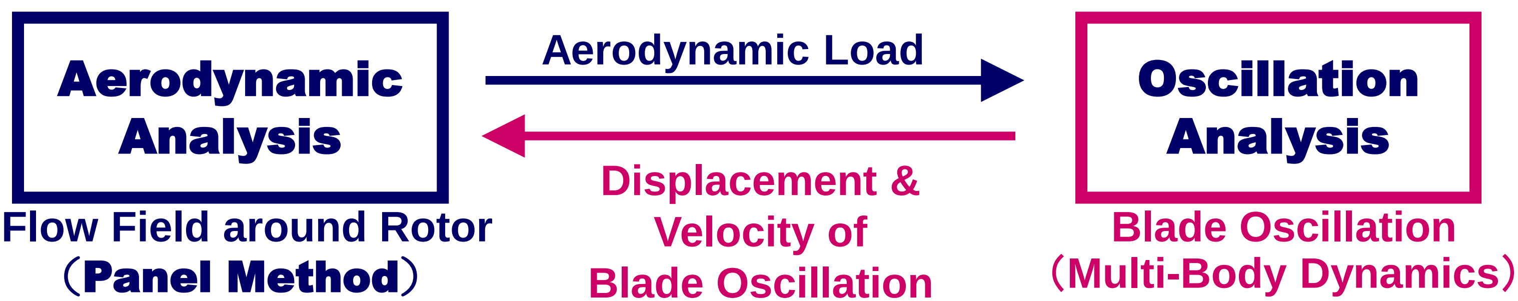


Yawed uniform inflow

Procedure II

- **Objective I :** Clarify the effects of **inflow condition** on blade loads by **simple analysis**

- **Procedure II :** Clarify the effects of **blade oscillation** on blade loads by **fluid-oscillation coupled analysis**



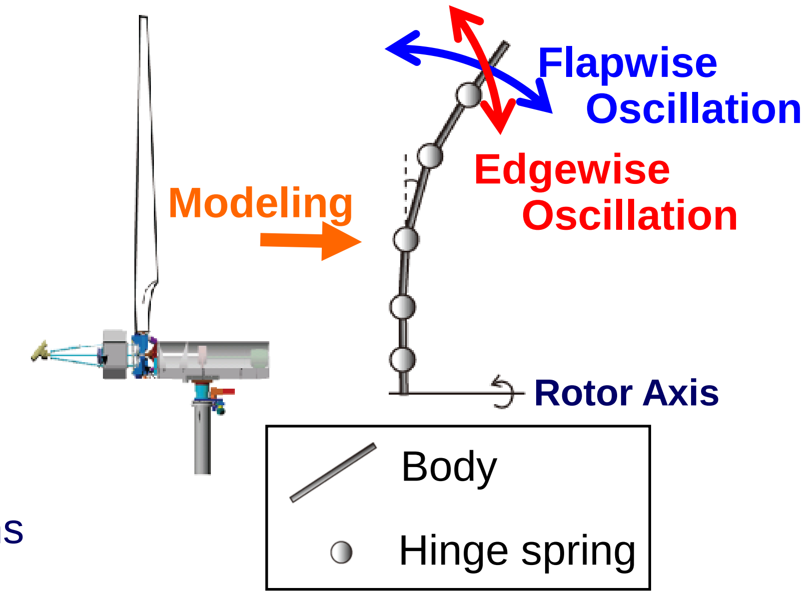
blades, wake vortices and tower are modeled by vortex lattices

<u>Two-way coupled analysis model</u>

Blade Oscillation Model

■ Multi Body Dynamics Model

- Represent rotor blade by combination of **Rigid Bodies** and **Hinge Springs**
- Consider forces on bodies **Aerodynamic, Gravity, Centrifugal, and Coriolis forces** as well as **Restoring and Damping Moments** from Hinges
- Examine **Flapwise** and **Edgewise** oscillations in the present study



Multi body dynamics

■ Verification of Oscillation Model

- Compare Eigen Frequencies of Static Blade

Mode	Calculation	Experiment
Flapwise 1 st	7.39 Hz	7.31 Hz
2nd	30.2 Hz	30.1 Hz
Edgewise 1 st	9.27 Hz	9.06 Hz
2nd	64.9 Hz	-

Validity of Oscillation model

Coupled Analysis Results

■ Blade Load Fluctuation in **Flapwise direction**

- **Aerodynamic Moment**

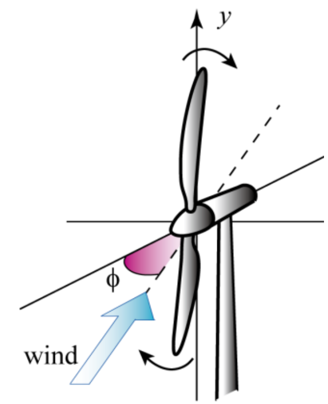
  Integrated moment due to aerodynamic force

  Exp. results are obtained from pressure distribution on blade.

- **Structural Bending Moment**

  Product of spring constant & bent angle
  of hinge spring at blade root

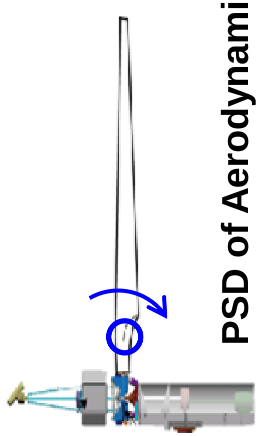
  Exp. results are obtained by strain gauge installed at blade root.

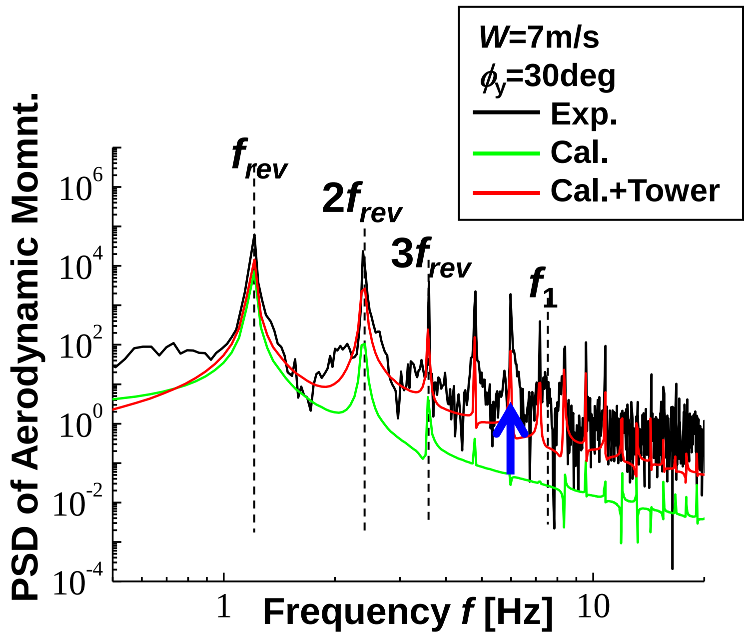


yawed inflow

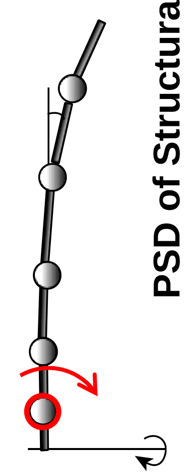
Rotation freq. f_{rev}=1.14Hz

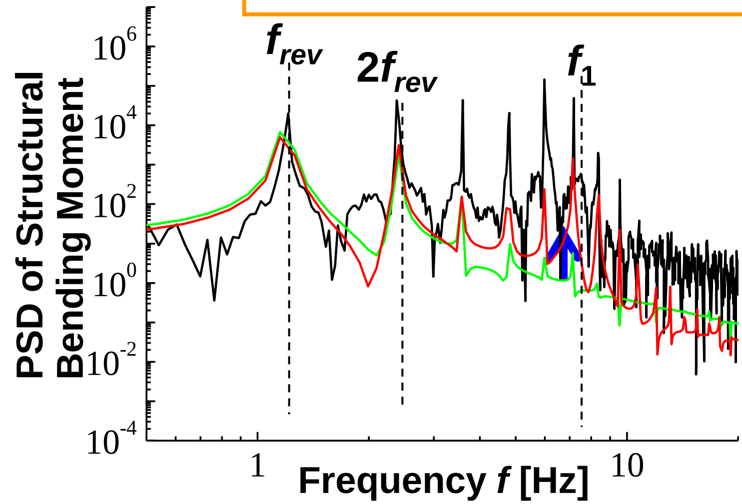
1st eigen freq. f_1=7.44Hz





Aerodynamic Moment

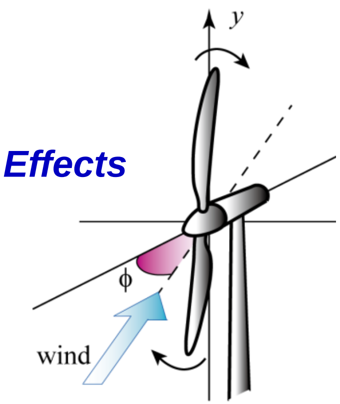




Structural Bending Moment

Coupled Analysis Results

■ Blade Load Fluctuation in **Flapwise direction**



yawed inflow

- **Aerodynamic Moment**

  Peaks at rotation freq. and its harmonics →***due to Rotational Sampling Effects***

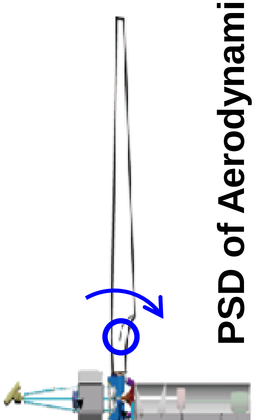
- **Structural Bending Moment**

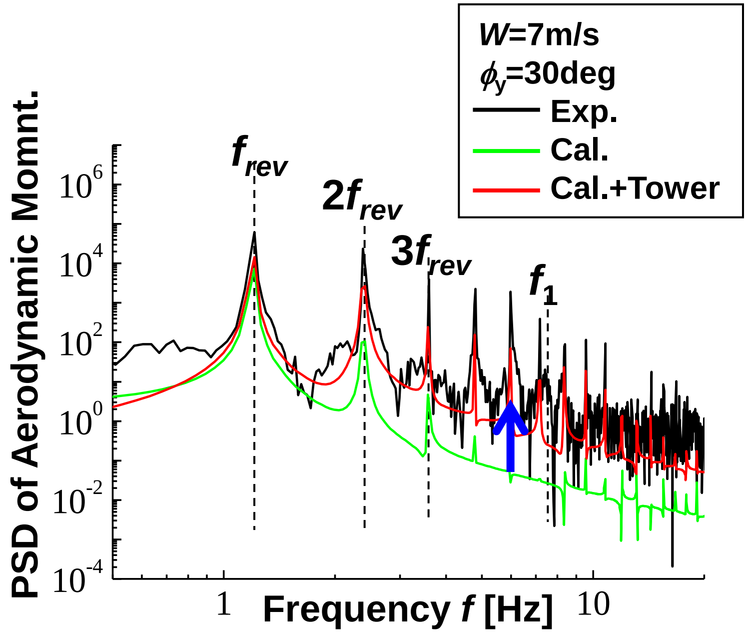
  Additional peak at 1st eigen freq. of blade structure

- **From comparison between Exp. and Cal.,**

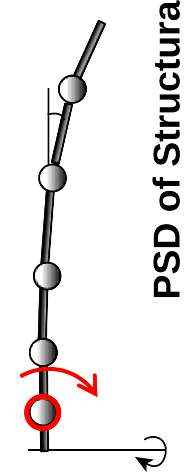
  Calculation results are improved by including tower model.

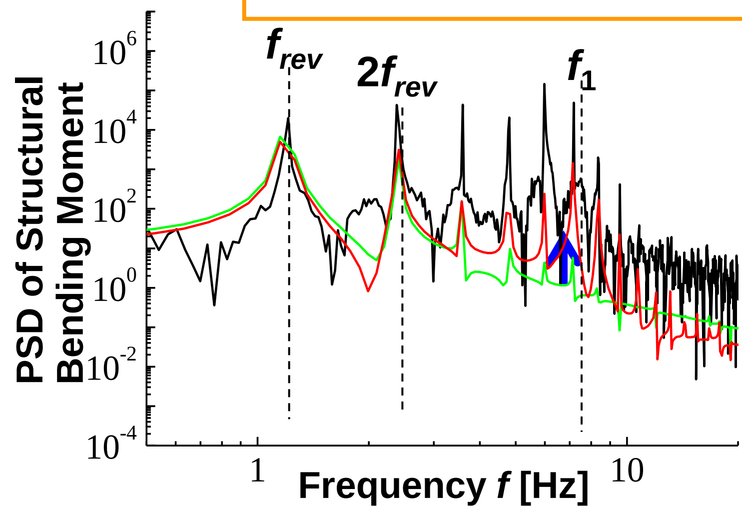
Rotation freq. f_{rev}=1.14Hz
1st eigen freq. f_1=7.44Hz





Aerodynamic Moment





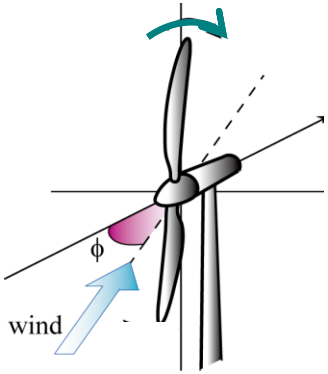
Structural Bending Moment

Coupled Analysis Results

■ Blade Load Fluctuation in **Edgewise direction**

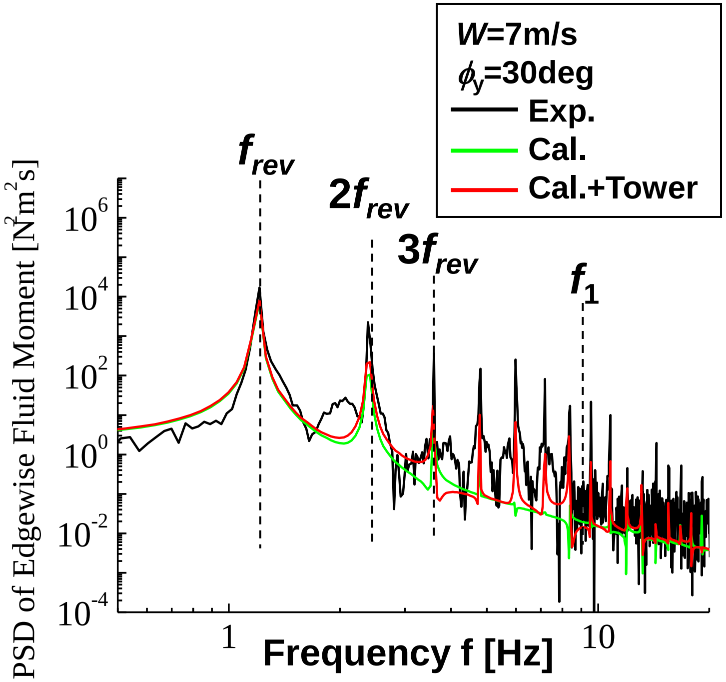
- **Aerodynamic Moment**
  Amplitude is much smaller than Structural Bending Moment
- **Structural Bending Moment**
  Gravitational Force Effects are dominant
- **Tower Effects on edgewise moment**
  Scarcely seen in calculated results

Edgewise dir.

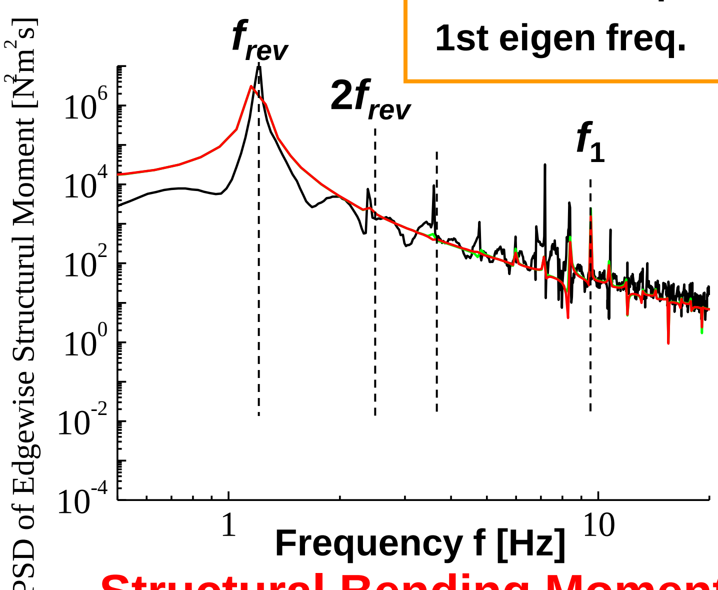


yawed inflow

Rotation freq. f_{rev}=1.14Hz
1st eigen freq. f_1=9.27Hz



Aerodynamic Moment



Structural Bending Moment

Summary I

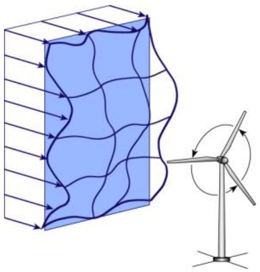
Inflow condition effects such as

- yaw misalignment
- turbulence

on fatigue load of HAWT rotor have been examined by simple numerical calculation.

■ For turbulent inflow condition,

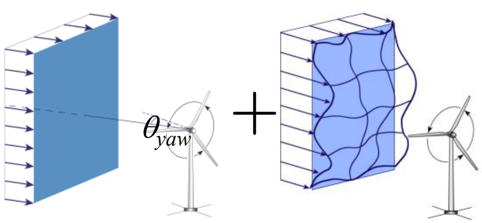
- **Longitudinal component of turbulence has dominant effects on fatigue load.**
- Effects from lateral and vertical components are negligible for fatigue load evaluation.



Turbulent inflow

■ For combined inflow condition of yaw misalignment and turbulence,

- Lateral and vertical components effects increase with yaw misalignment angle.
- **3d turbulence is necessary for fatigue load calculation.**



Yawed turbulent inflow

Summary II

A fluid-oscillation coupled analysis model has been constructed for the estimation of the flapwise and the edgewise blade loads of HAWT rotor.

- Validity of the coupled analysis model is improved **by introducing the tower model** into the aerodynamic calculation **for flapwise component.**

- Tower effects can scarcely be seen **in the edgewise structural moment**, which is dominated by the gravitational force.

Aerodynamic Analysis → Aerodynamic Load → **Oscillation Analysis**

Oscillation Analysis → Displacement & Velocity of Blade Oscillation → **Aerodynamic Analysis**

<u>**Two-way coupled analysis model**</u>

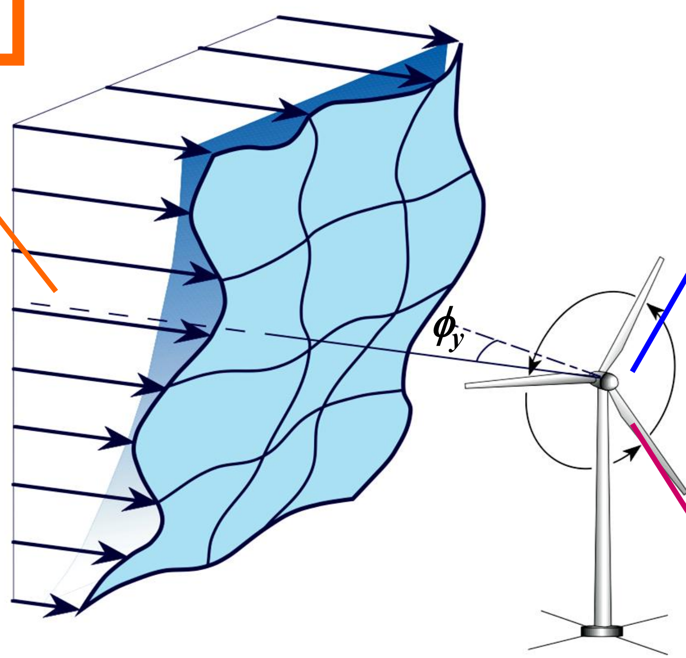
Our Future Work I

■ Design of Turbine Control

- Include power-train model
- Decrease fatigue load, power fluctuation
- Suppress structural oscillation

Inflow Wind Model

Aerodynamic Load Calculation Model



Coupled Analysis

Power-Train Model

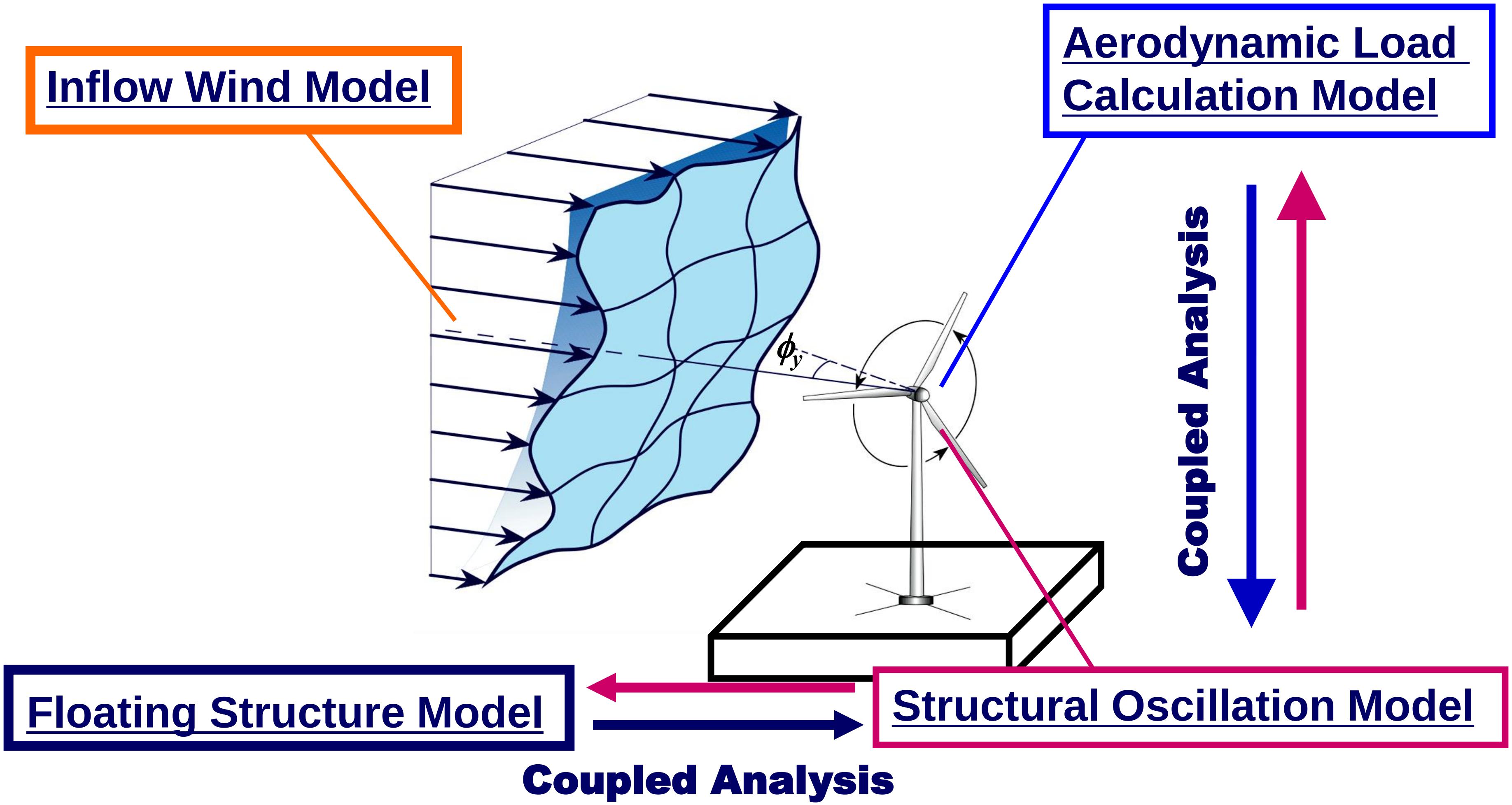
Structural Oscillation Model

Coupled Analysis

Our Future Work II

■ Application to Off-shore Turbine

- Include floating structure model



Thank you for your kind attention . . .