Response Analysis of Wind Turbine Support Structures Using Measured Wind Speed

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Introduction

With the rapid increase of wind energy in Japan, accidents of the wind turbines are reported. It is important to estimate the responses of the turbine support structures accurately. As wind load is one of the most prevailing load, wind generation for the dynamical simulation of the turbine support structures are an important issue. Conventional wind generation methods use the statistical wind data such as mean wind speed, turbulence intensity, the spectrum of turbulence and spatial correlation. With this conventional method, the mean response and the standard deviation of the fluctuating response can be simulated accurately. However, the estimation of the maximum response has problem. In this study, a wind generation method which uses the measured wind speed at the nacelle is applied to the response analysis of wind turbine and verified by the measurement.

Model Overview

Finite Element Method Model

In this research, CAsT (Computer-Aided Aerodynamic and Aero-elastic Technology) is used to estimate response[1].

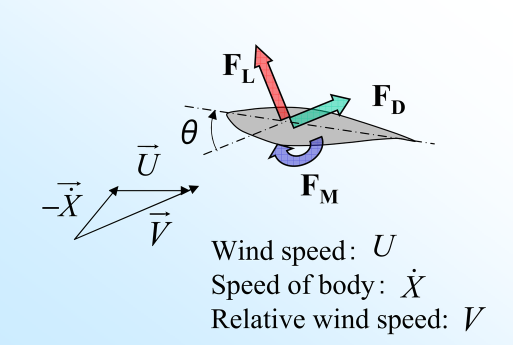
$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}$$

Where, $\mathbf{M}$ is a mass matrix, $\mathbf{C}$ is a damping matrix, $\mathbf{K}$ is a stiffness matrix, $\mathbf{f}$ is a aerodynamic force vector of the nodal point, $\mathbf{x}$ is displacement vector of the nodal point.

Aerodynamic force can be obtained by considering relative wind speed.

$$F_D = \frac{1}{2}\rho A C_D(\alpha)(|u-\dot{x}|)^2,\ F_L = \frac{1}{2}\rho A C_L(\alpha)(|u-\dot{x}|)^2$$

Where, F_D is drag force and F_L is lift force, ρ is air density, A is the area, C_D is the drag coefficient and C_L is the lift coefficient in terms of angle of attack, α.



Aerodynamic force and angle of attack

Overview of response analysis program, CAsT

Numerical Integration	Newmark- β Method
Eigenvalue Analysis	Subspace Iteration Method
Model	Beam Model including Saint-Venant Twist
Reference Coordinate System	Total Lagrange Formulation
Evaluation of Aerodynamic Force	Quasi-steady Aerodynamic Theory
Structural Damping	Rayleigh Damping

Generation of Wind

Iwatani method[2] is expanded to consider lateral and vertical fluctuating velocity components as well as longitudinal component.

Iwatani's AR Model

$$\mathbf{u}(t) = \sum_{m=1}^{M} \mathbf{A}(m)\mathbf{u}(t - m\Delta t) + \mathbf{n}(t)$$

$$\mathbf{u}(t) = {}^t(u_1(t), u_2(t), \cdots, u_K(t)) \qquad \mathbf{n}(t) = {}^t(\varepsilon_1(t), \varepsilon_2(t), \cdots, \varepsilon_K(t))$$

Where, $\mathbf{M}$ is the number of past data, $\mathbf{K}$ is the number of nodes, m is the index of time, Δt is time interval of the data. $\mathbf{u}(t)$ is the time series of wind fluctuations and $\mathbf{n}(t)$ is the time series of random component. Each element of $\mathbf{A}(m)$ is the correlation coefficient of the multi-dimensional nodes.

Expanded Model

$$\mathbf{u}^P(t) = \sum_{q=1}^{3}\left[\sum_{m=1}^{M} \mathbf{A}^{pq}(m)\cdot \mathbf{u}^q(t - m\Delta t)\right] + \mathbf{n}^p(t)$$

Where, p denotes wind direction components (p=1,2,3 corresponding to longitudinal, lateral, vertical wind direction, respectively)

Matrix $\mathbf{A}$ can be calculated by solving the following equation.

$$\begin{bmatrix}\mathbf{R}(1) & \mathbf{R}(2) & \cdots & \mathbf{R}(M)\end{bmatrix} = \begin{bmatrix}\mathbf{A}(1) & \mathbf{A}(2) & \cdots & \mathbf{A}(M)\end{bmatrix} \times \begin{bmatrix}\mathbf{R}(0) & \mathbf{R}(1) & \cdots & \mathbf{R}(M-1) \\ \mathbf{R}(-1) & \mathbf{R}(0) & \cdots & \mathbf{R}(M-2) \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{R}(1-M) & \mathbf{R}(2-M) & \cdots & \mathbf{R}(0)\end{bmatrix}$$

$$\mathbf{R}(r) = \begin{bmatrix}R^{11}(r) & R^{12}(r) & R^{13}(r) \\ R^{21}(r) & R^{22}(r) & R^{23}(r) \\ R^{31}(r) & R^{32}(r) & R^{33}(r)\end{bmatrix} \qquad R^{pq}(r) = \overline{p(t-m\Delta t)\, q(t-(m+r)\Delta t)}$$

Vector $\mathbf{n}$ can be calculated by solving the following equation.

$$\mathbf{n}(t) = \mathbf{L}\cdot\mathbf{o}(t) \qquad \mathbf{D} = \mathbf{L}\cdot{}^t\mathbf{L} \qquad \mathbf{D} = \mathbf{R}(0) - \sum_{m=1}^{M}\mathbf{A}(m)\,{}^t\mathbf{R}(m)$$

Generation of Wind Using Measurements

The wind speed measured by nacelle anemometer is used to improve the generation of wind field.

When calculating the random component $\mathbf{n}(t)$, eauation

$$\mathbf{n}(t) = \mathbf{L}\cdot\mathbf{o}(t)$$

can be written as

$$\begin{bmatrix} n_1(t) \\ \vdots \\ n_l(t) \\ n_{l+1}(t) \\ \vdots \\ n_K(t) \end{bmatrix} = \begin{bmatrix} L_{11} & & & & & 0 \\ \vdots & \ddots & & & & \\ L_{l1} & \cdots & L_{ll} & & & \\ L_{l+11} & \cdots & L_{l+1l} & L_{l+1l+1} & & \\ \vdots & \ddots & \vdots & \vdots & \ddots & \\ L_{K1} & \cdots & L_{Kl} & L_{Kl+1} & \cdots & L_{KK} \end{bmatrix} \begin{bmatrix} o_1(t) \\ \vdots \\ o_l(t) \\ o_{l+1}(t) \\ \vdots \\ o_K(t) \end{bmatrix}$$

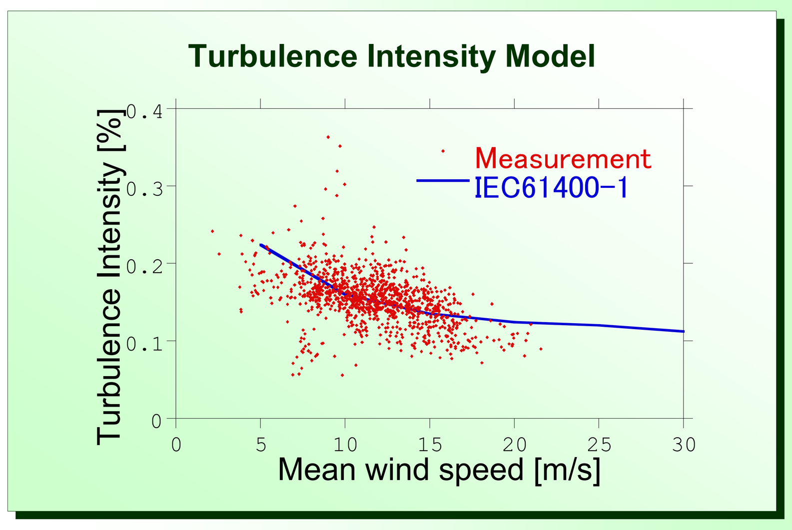
If measured wind speed is given, the $n_1(t),\cdots,n_l(t)$ can be obtained by AR model. In addition, $o_1(t),\cdots,o_l(t)$ can be obtained by the upper part of the below equation. Then, $n_{l+1}(t),\cdots,n_k(t)$ can be obtained by the lower part.

The time series of wind fluctuations for all points as well as the reference point can be obtained by using $n_{l+1}(t),\cdots,n_k(t)$

Verification

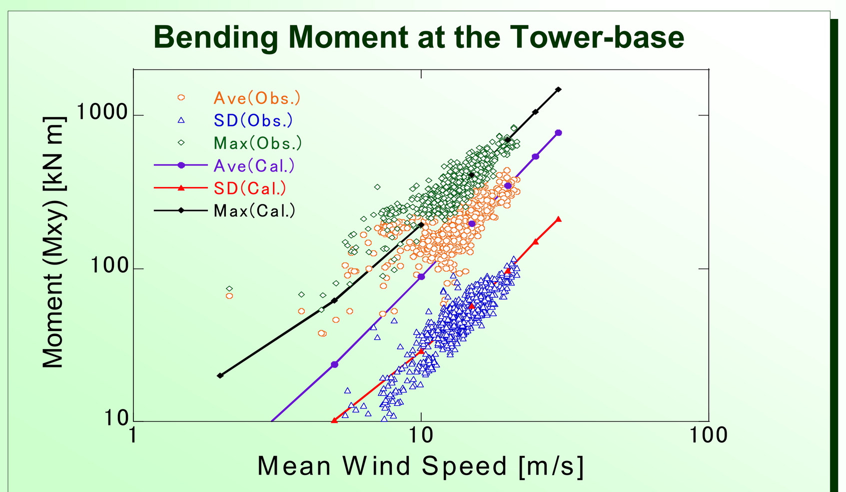
Modeling for Turbulence Intensity

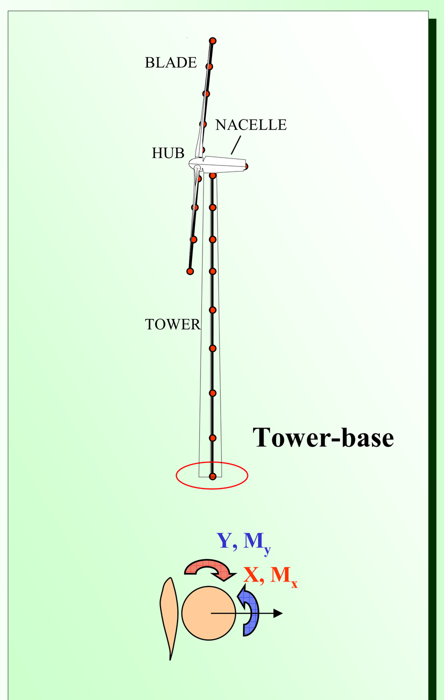
For the turbulence intensity, IEC model was used which shows good agreement with the measurement.



Verification of the Simulated Moments

For verification of the model, simulated moments were compared with the measurements.





Wind turbine beam model

The predicted tower-base bending moments shows good agreement with the measurement.

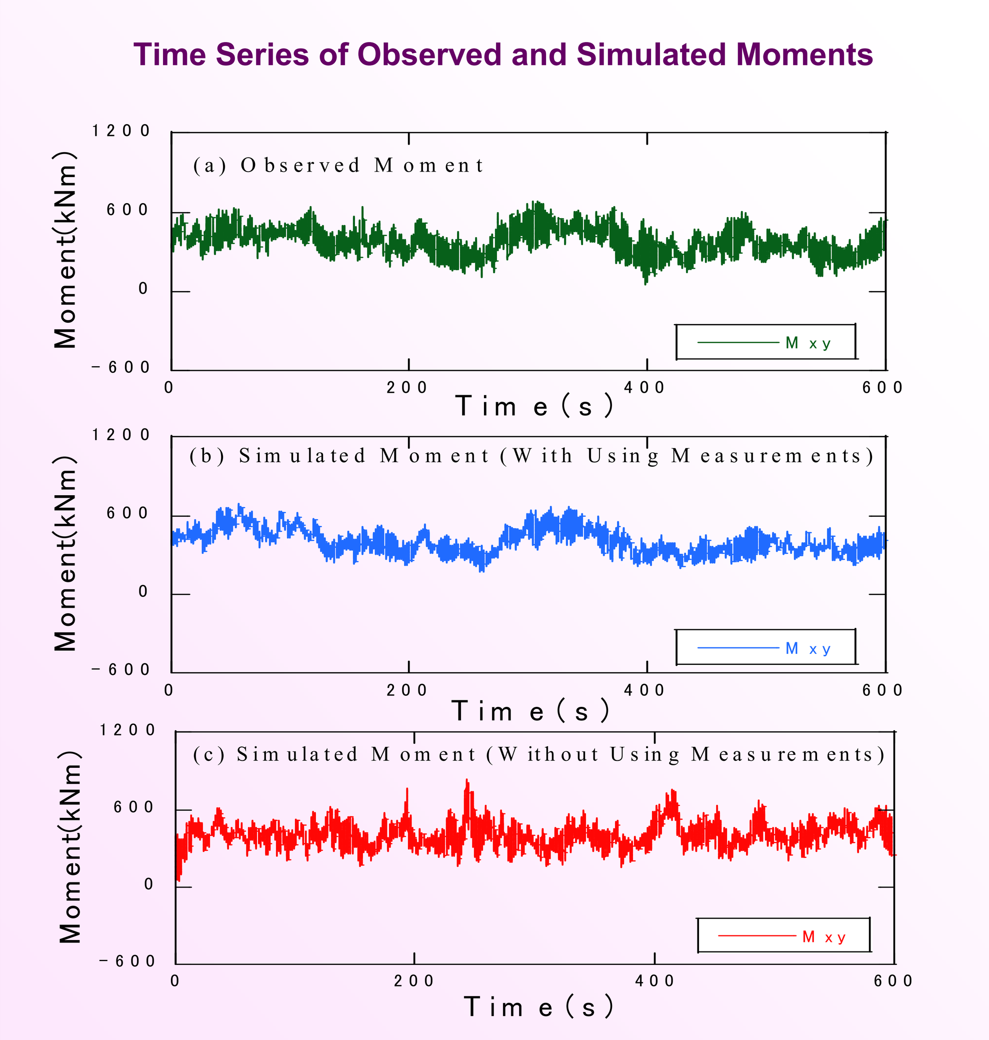
Response Using Measured Wind Speed

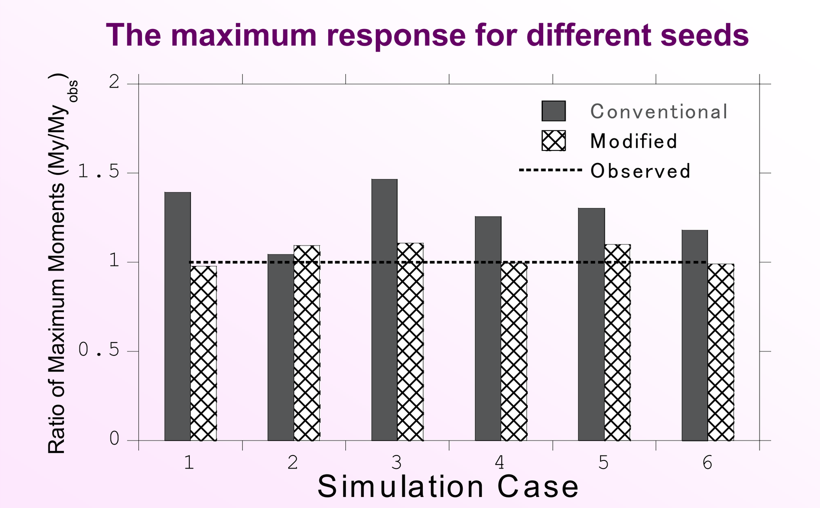
Results

Time series of observed and simulated moments, statistical data including correlation coefficients, and the ratio of two estimated maximum moments to observed maximum moment for 6 simulation cases are shown to verify that responses using measured wind speed are steady and accurate.

Comparison of the simulation and the measurement

	Observation	Modified	Conventional
Mean	376.56	402.36	403.32
Standard Deviation	99.61	93.18	94.49
Maximum	678.58	684.94	828.12
Correlation Coefficient		0.603	0.143





The results indicate that predicted maximum bending moments at the tower base show good agreements with measurements and correlation coefficients between observed and simulated moments increase from 0.143 to 0.603, when measured wind speed is used.

Conclusions

In this study, the response analysis of wind turbine support structures are carried out and following results were obtained.

1. The prediction of the mean and fluctuating component of the tower-base bending moments shows good agreement with the measurement regardless the use of the measured wind speed for the wind generation.
2. On the other hand, the predicted maximum bending moments showed better agreement with the measurements when the measured wind speed is used for the generation of wind and correlation coefficients between observed and simulated moments increase from 0.143 to 0.603.

Reference

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2) Iwatani, Y. (1982), "Simulation of Multidimensional Wind Turbulences Having Any Arbitrary Power Spectra and Cross Spectra", J. Wind Engineering, 11, 5-17 (in Japanese).
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4) IEC 61400-1 (2005), Wind Turbines-Part 1: Design Requirements, 3rd Edition.