PO.ID 080

Load estimation of an offshore wind turbine support structure during operation and validation by measurement

Prasanti Widyasih Sarli , Atsushi Yamaguchi, Takeshi Ishihara
The University of Tokyo

Abstracts

Extreme wind load during power production is an important load case for the design of offshore wind turbine. Typically, dynamic simulation is carried out to estimate extreme wind load during power production[1], but the validation of those dynamic simulation is limited. For the design of tower and foundation, an analytical model for tower moment is proposed but this model is only validated at the tower base[2]. In addition, the statistical load extrapolation of wind load, widely used to estimate the maximum wind load during power production, contains large uncertainty[3,4] therefore in order to obtain stable results, new method for convergence criteria is needed.

This study therefore focuses on the validation of dynamic simulations, analytical mode for tower base moment for different heights and a new convergence criteria for load extrapolation.

Dynamic Simulation and Validation

Modeling

A 2.4MW Wind Turbine was modeled by using GH Bladed.

Source of model parameters

Manufacturer	JSCE Guideline[5]	Measurement
• Dimension of Nacelle • Blade length, twist angle and weight • First mode frequency of blade • Dimension and weight of tower	• Control algorithm • Aerodynamic property of blade	• Frequency and damping of the 1st and 2nd tower mode

Control Model

$$\Delta Q_{Dem} = 750.67y + 170y_1$$

$$\Delta\theta_{Dem} = \kappa(0.018884y + 0.008226y_1)$$

Where two different gain scheduling κ algorithms were used either constant or

$$\kappa = min\left[\frac{1}{\frac{\xi}{\kappa_{out}} + (1-\xi)}, 1\right] \qquad \xi = \frac{\theta - \theta_{des}}{\theta_{out} - \theta_{des}}$$

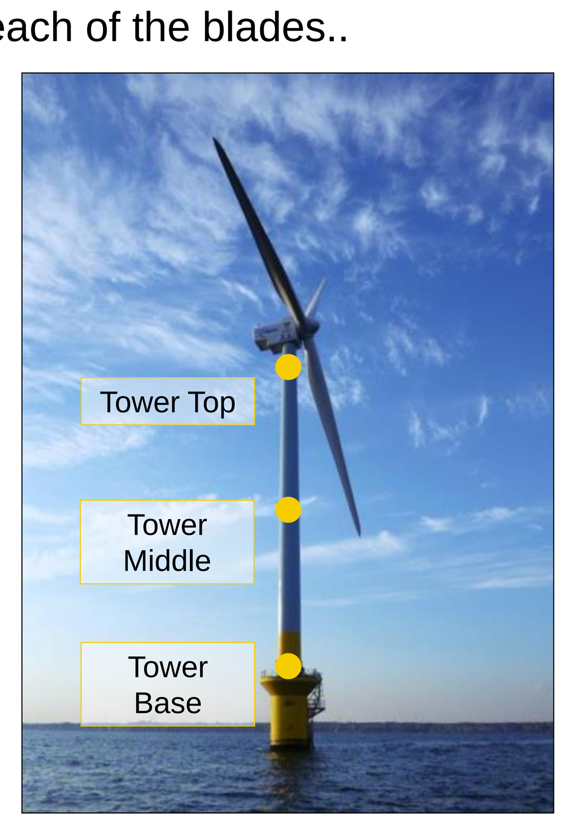
ΔQ_{Dem}=Demanded Torque
$\Delta\theta_{Dem}$=Demanded Pitch
y=deviation of generator speed
y_1=residual of generator speed
κ_{out}=cut out wind speed reduction factor, 1/3
θ_{out}=cut out wind speed pitch angle, 90 degrees
θ_{des}=pitch angle design, 4.5 degrees

Rotor Mass Imbalance

Rotor mass imbalance was added to account for the difference in mass and center of gravity of each of the blades..

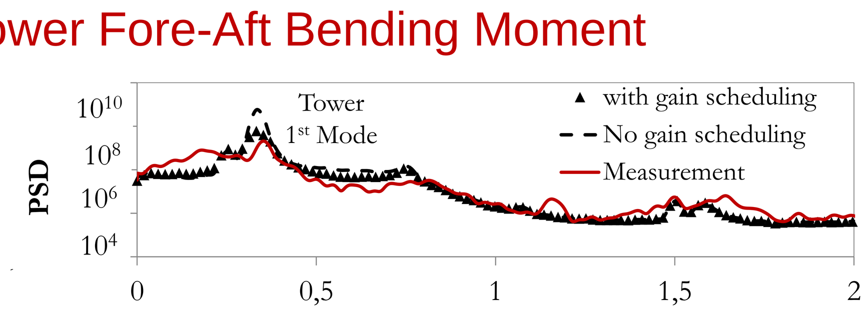
Measurement

- Strain Gauges are put at 3 different levels of the tower
- Measurements are bin average of the maximum load in each 10 minutes of 4 months data (September 2013- December 2013)



Observed Choshi 2.4MW Wind Turbine (NEDO/TEPCO)

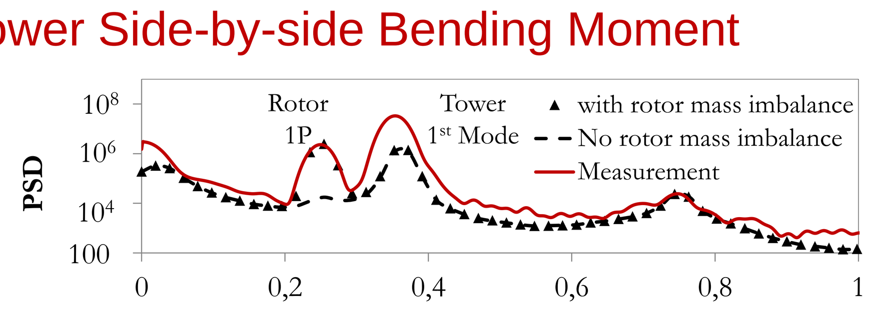
Tower Fore-Aft Bending Moment



PSD comparison of the tower fore-aft moment

Without considering gain scheduling there will be overestimation in the effect of the 1st tower natural frequency.

Tower Side-by-side Bending Moment



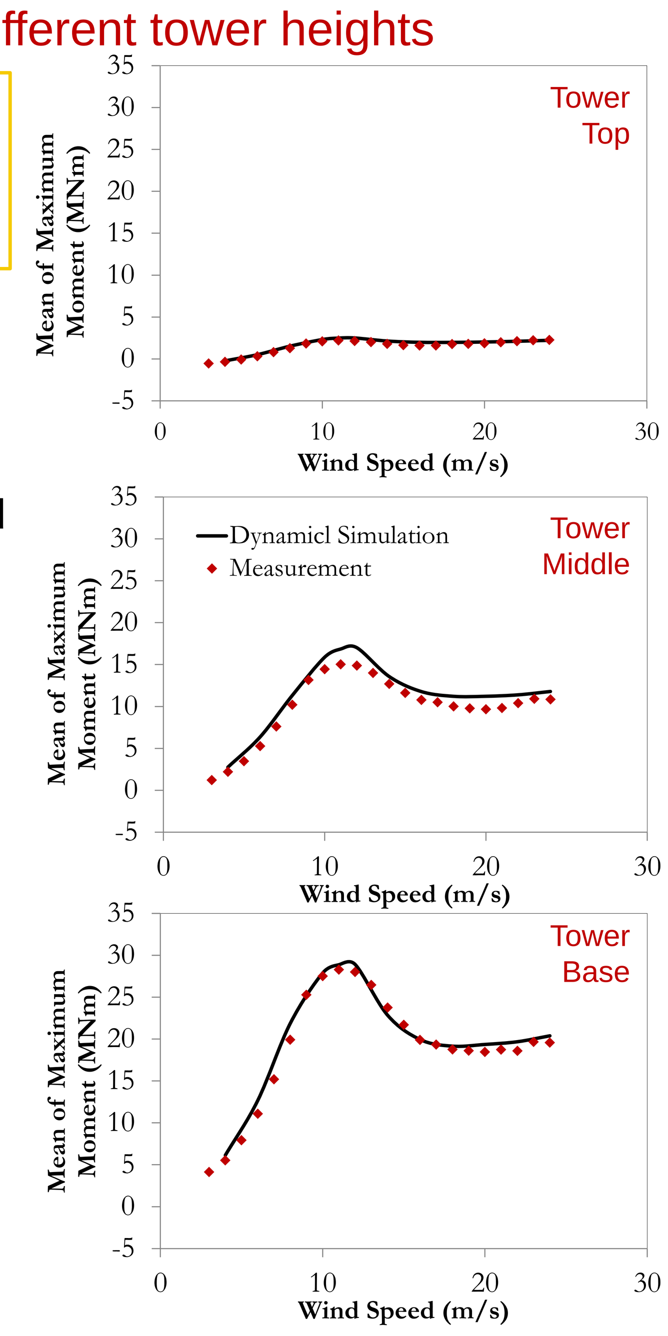
PSD comparison of the tower base side-by-side moment

Without considering rotor mass imbalance there will be underestimation in the frequencies related to the rotor rotation

Load distribution at different tower heights

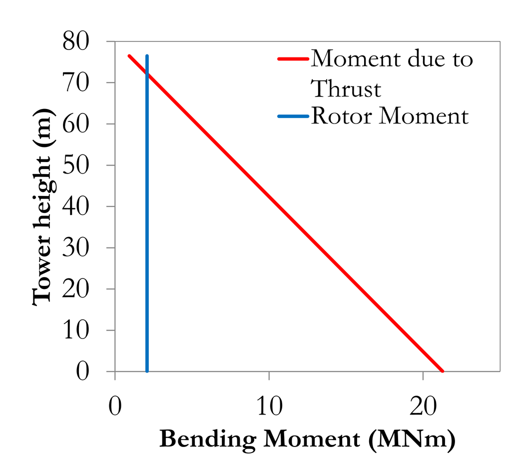
Simulation shows good agreement with measurement

The dominant wind speed at the tower base to tower top changes; the tower base is dominated by rated wind speed while the tower top is dominated by the cut out wind speed.



Mean of the maximum bending moment at different heights of the tower

The tower base is dominated by thrust force while the tower top is dominated by rotor moment.



Change of thrust force at different heights of tower compared to rotor moment

Modeling of Tower Moment

Modeling of Tower Maximum Bending Moment

$$M_{maxTower} = \bar{M}_T + s\bar{M}_R + \sqrt{P_T\sigma_T^{\,2} + sP_R\sigma_R^{\,2}}$$

$\bar{M}_R$ = mean rotor moment
σ_R= standard deviation of rotor moment
P_R= peak factor of rotor moment, taken at 3.5
s= rotor moment scaling factor depending on the diameter of the rotor, $D^3/_{D3}$

The modeling of the components related to thrust force, such as the mean $\bar{M}_T$,peak factor P_T and standard deviation σ_T has already been proposed by Ishii and Ishihara [2]

Rotor Moment Modeling

$$\bar{M}_R = 0.022u - M_g \qquad \sigma_R^{\,2} = RMS_R^{\,2} - \bar{M}_R^{\,2}$$

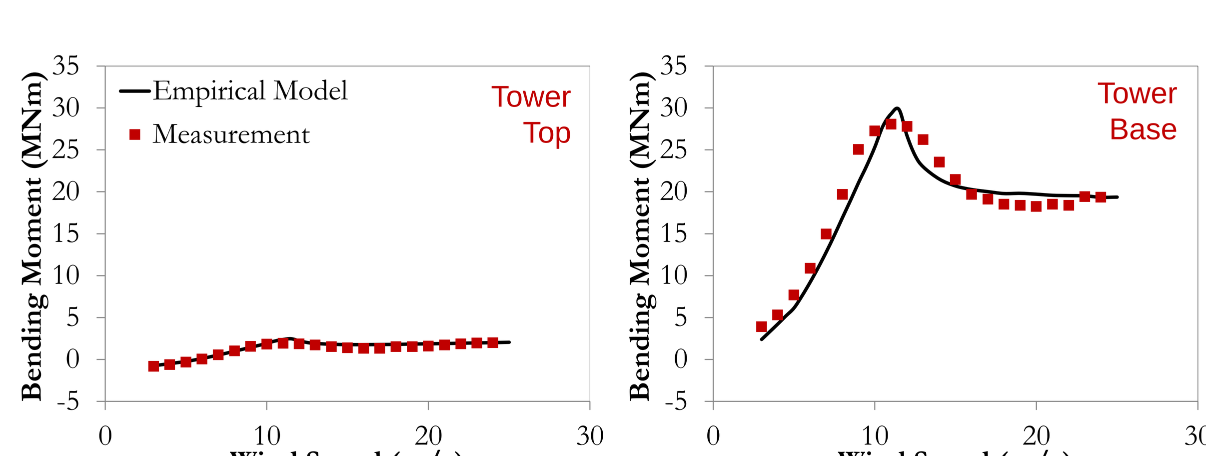
$$RMS_R = f_1(u)\, I_{reff} + f_2(u)$$

$$f_1(u) = -0.0028u^2 + 0.1798u + 0.8897$$

$$f_2(u) = 0.0192u - 0.0765$$

$\bar{M}_R$ = mean rotor moment (MNm)
M_g = moment due to gravity load
u = wind speed (m/s)
RMS_R = root mean square of the rotor moment
I_{reff} =expected value of turbulence intensity at 15 m/s.

Validation of Model



Mean of maximum tower bending moment modeling

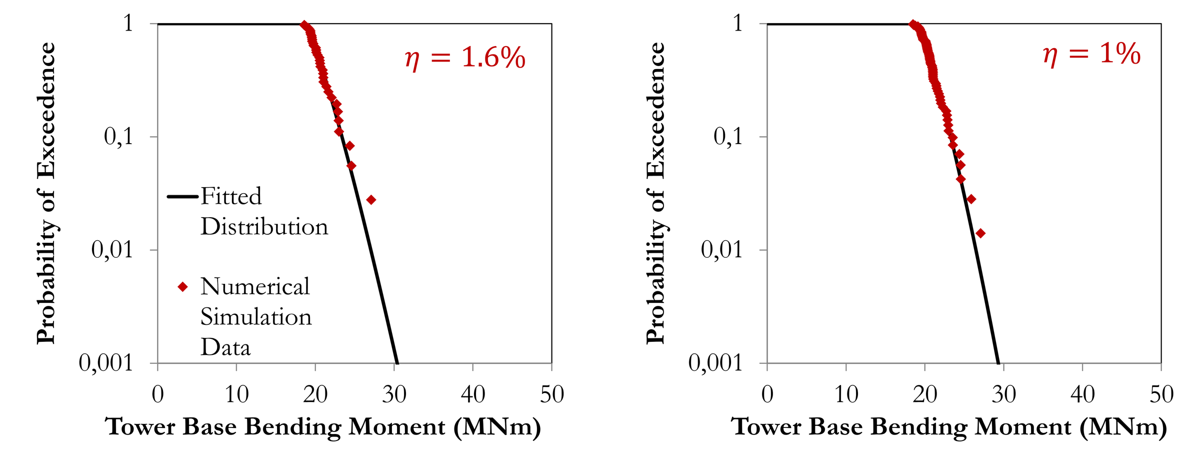
The model gives good load estimation for different tower heights

New Convergence Criteria for Load Extrapolation

A new convergence criteria based on the difference between simulated load and the load based on estimated distribution function is proposed.

$$\eta = \frac{\epsilon}{s_{ave}}; \qquad \epsilon = \sqrt{\sum_{j=1}^{N}\frac{(s_{sim-j} - s_{fit-j})^2}{N}}$$

η = relative error
ϵ= error
s_{ave}= average of all loads
N=number of data
s_{sim} = load response from simulation
s_{fit} = load response from the fitted distribution

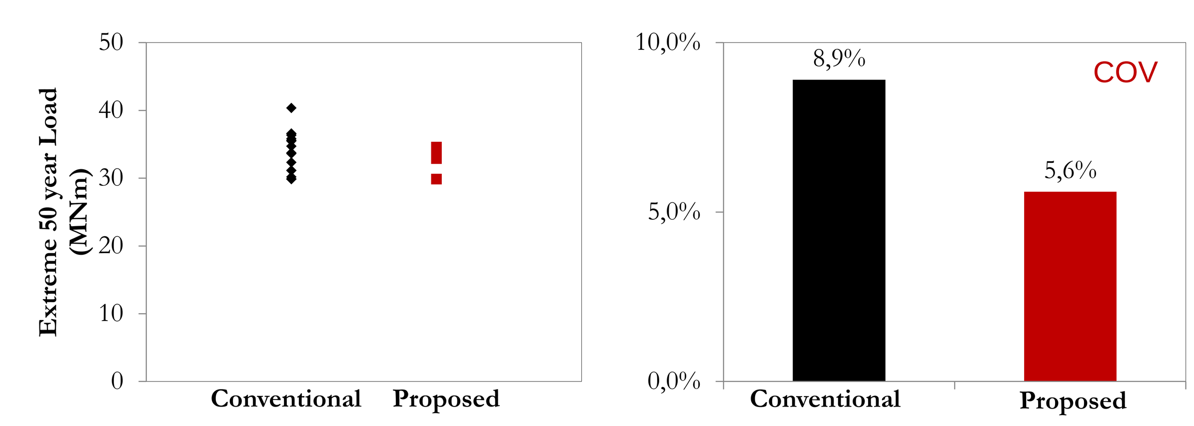


Probability of exceedance before and after convergence

- Start from 35 simulations for each wind speed.
- If $\eta \geq 1\%$, double the number of simulation

- Converged when $\eta \leq 1\%$

Under each convergence criteria, maximum load for 50 years recurrence period was estimated.



Extreme 50 year load by using the conventional and proposed method

The uncertainty of the extrapolation load is reduced

Conclusions

1. Dynamic simulation of an offshore wind turbine was validated by using measurement data. Overestimation of fore-aft tower base moment was improved by using gain scheduling. The underestimation of side-side tower base moment was improved by considering rotor mass imbalance. The tower base moment is dominated by thrust force on rotor, while the tower top moment is dominated by the moment on the rotor.
2. The modeling of the tower moment based on thrust force and rotor moment was proposed. The model shows good agreement with measurement.
3. A new convergence criterion was proposed for load extrapolation. By using the proposed model, the coefficient of variation of the extreme 50 years load was reduced.

Acknowledgements

This research was funded by NEDO (New Energy and Industrial Technology Development Organization) and Tokyo Electric Power Company. The wind turbine data was proposed by Mitsubishi Heavy Industry. and TEPCO.

References

1. Moriarty, Patrick. (2008), "Database for validation of design load extrapolation techniques", Wind Energy11:559-576.
2. Ishii H, and Ishihara T. (2010) "Numerical Study of Maximum wind load on wind turbine tower under operating condition", CWE2010
3. Tarp-Johansen, Madsen P. and Frandsen S. (2002) "Partial Safety Factors for Extreme Load Effects", Riso National Laboratory
4. International Electronical Commission (Amendment 2008) IEC 61400-1-Part 1 : Design Requirements Ed.3,55-60
5. JSCE (2010),"Guidelines for design of wind turbine support structures and foundations", Japan Society of Civil Engineers (in Japanese)