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Seismic Load Evaluation of Wind Turbine Support Structures with Consideration of Uncertainty in Response Spectrum and Higher Modes

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Objectives

Rapid development of wind energy in seismically active regions like Japan requires evaluation of design seismic load of wind turbine support structures to ensure structural integrity. Analytical estimation of the design loads is usually carried out by the response spectrum method that encounters two problems when used for load analysis of wind turbine support structures[1]. These support structures are extremely low damped that experience a wide range of frequencies when subjected to seismic activities. Response spectrum for such low damped structures show excessive fluctuation and such uncertainty in response spectrum can not be captured by existing models of the damping correction factors defined in Eurocode[2] and BSL[3]. In addition, use of the simplified SDOF model suggested by IEC[4] results in linear vertical load profiles. However, vertical distribution of the seismic loads is found to be largely affected by the higher modes[1] of wind turbines. Therefore simplified but accurate analysis method to estimate design load profiles is desired.

In this research, model for damping correction factor that accounts for uncertainty in response spectrum, and modal participation functions encompassing complex vertical distribution of seismic loads are proposed. The accuracy and reliability of the proposed method for evaluation of seismic design loads is examined against time history analysis and current design codes.

Response Spectrum Method

Eqation of motion for jth mode of a MDOF system is,

$$\ddot{q}_j + 2\zeta_j\omega_j q_j + \omega_j^2 q_j = -\gamma_j \ddot{x}_g$$

Here, ω_j, ζ_j and γ_j are natural frequency, damping ratio and mode participation factor of jth mode. Force for each mode of vibration is calculated as follows:

$$F_{ij} = \gamma_j X_{ij} S_a(T_j, \zeta) m_i$$

Seismic force depends upon:

a. acceleration of response spectrum (S_a) of SDOF

b. modal participation function ($\gamma_j X_{ij}$)

Design acceleration response spectrum[2] is defined as:

$$S_a(T,\zeta) = \begin{cases} a_0 \cdot S \cdot \{1 + \frac{T}{T_B} \cdot (\beta_0 \cdot F_\zeta - 1)\} & (0 \le T < T_B) \\ a_0 \cdot S \cdot F_\zeta \cdot \beta_0 & (T_B \le T \le T_C) \\ a_0 \cdot S \cdot F_\zeta \cdot \beta_0 \cdot \left(\frac{T_C}{T}\right) & (T_C < T) \end{cases}$$

Parameters for a return period of 500 years[5]

a_0 (m/s^2)	S	β_0	T_B (s)	T_C (s)
3.2	1.5	2.5	0.16	0.576

where a_0 is design ground acceleration, S is soil amplification factor and F_ζ is damping correction factor.

Eurocode[2] defines the damping correction factor as a function of damping ratio so that,

$$F_\zeta(\zeta) = \left(\frac{7}{2 + 100\zeta}\right)^\alpha, \quad \alpha = 0.5$$

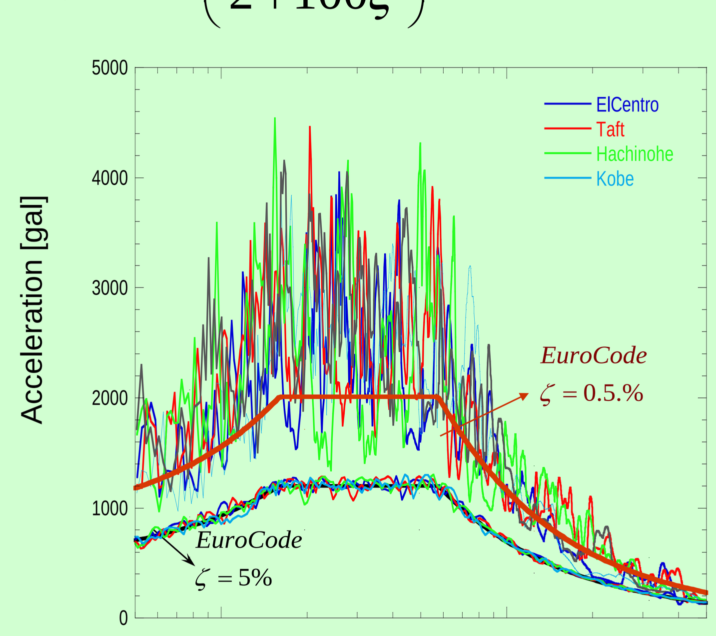


Fig. Response spectrum for Level II earthquake

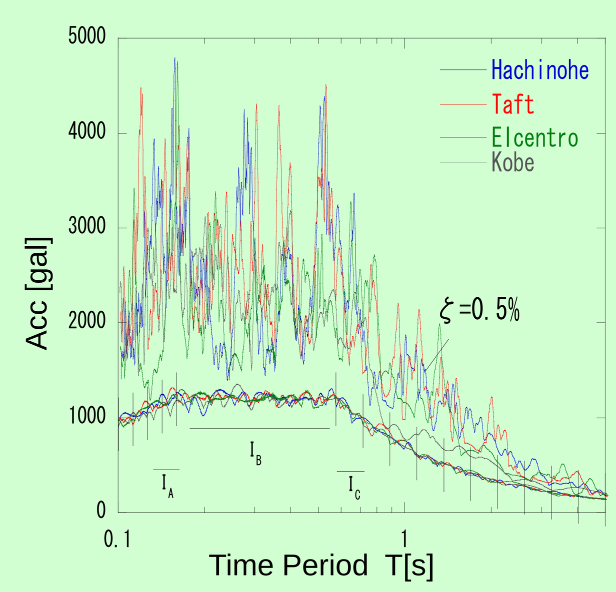
However, in case of the wind turbine support structures that are significantly low damped, this model fails to estimate large fluctuations of the spectral acceleration in order to establish reliable design spectrum.

Model for Damping Correction Factor

To account for excessive fluctuations in the response spectrum of low damped systems, damping correction factor is proposed as a function of spectral uncertainty (γ), natural period (T) and damping ratio(ζ) so that,

$$F_\zeta(\zeta, T, \gamma) = \left(\frac{7}{2 + 100\zeta}\right)^\alpha, \quad \alpha = f(T, \gamma)$$

A set of 35 seismic waves, with observed and random phases, is used to evaluate uncertainty in acceleration response spectrum for damping ratios ranging from 0.5 to 5%.



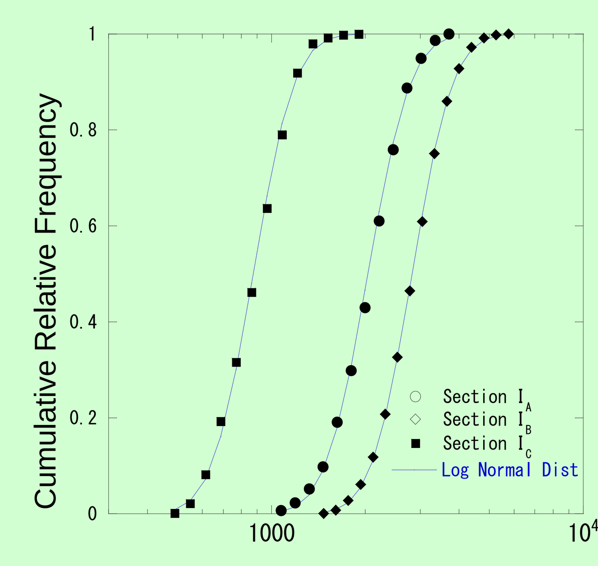


Fig. Segments for Statistical analysis Fig. CRF of acc. for each section

The log normal distribution is found to have well defined uncertainty in all sections of the acceleration response spectrum as shown in above figure. Investigations to identify exponent α has shown linear relationship with quantile (γ) and natural period (T) that lead to following:

$$F_\zeta(\zeta, T, \gamma) = \left(\frac{7}{2 + 100\zeta}\right)^\alpha, \quad \alpha = -0.07T + 0.7\gamma + 0.5$$

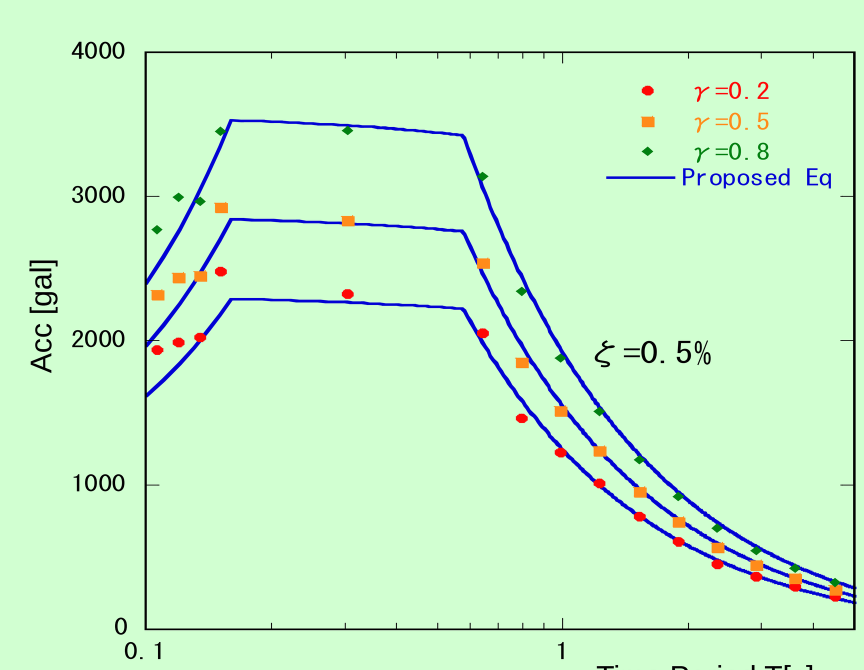


Fig. Variation of response spectrum with γ-values

Proposed damping correction factor shows good agreement with analytical one for all quantiles. Also proposed model performs well for both low and highly damped structures whereas EuroCode underestimates spectral acceleration for low damped systems.

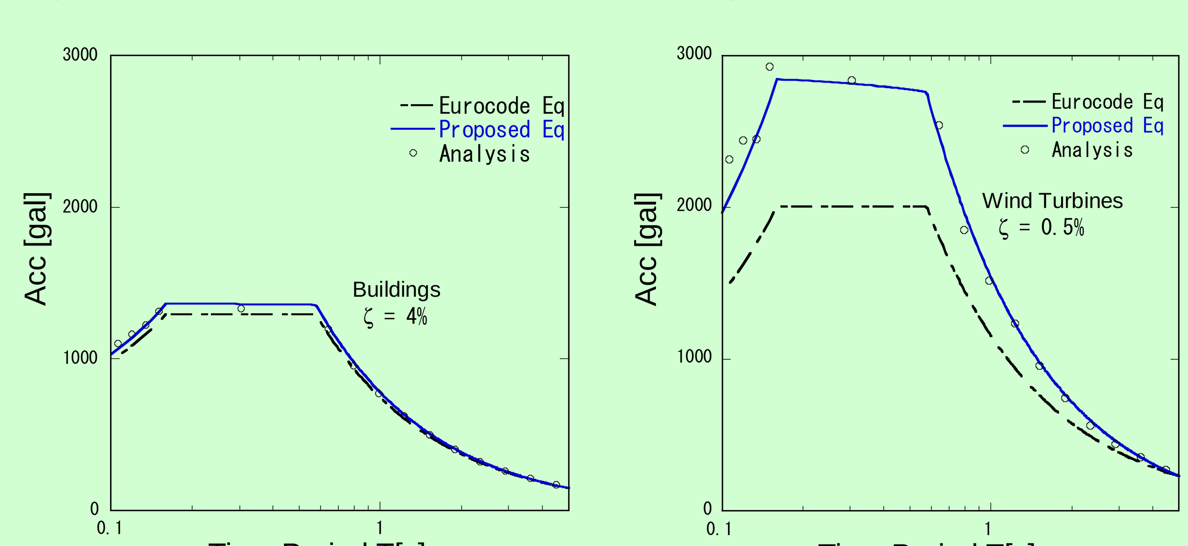


Fig. Comparison of current and proposed model

Formula for Vertical Profile of Seismic Loads

Estimation of design loads require natural periods and modal participation function ($\gamma_j X_{ij}$) of the dominant modes. Since first three modes accounted for modal mass of 85%[4], expression for calculating the respective model participation function and coefficients are listed below:

$$\gamma_j X_{ij} = \sum_{k=1}^{3} c_{jk} \left(\frac{z_i}{H}\right)^{k+1}$$

Coefficients and time period ratio

j \ k	c_{jk} 1	c_{jk} 2	c_{jk} 3	T_j / T_1
1	1.1	0	0	1
2	5.87	-6.00	0	0.127
3	14.26	-38.20	24.00	0.043

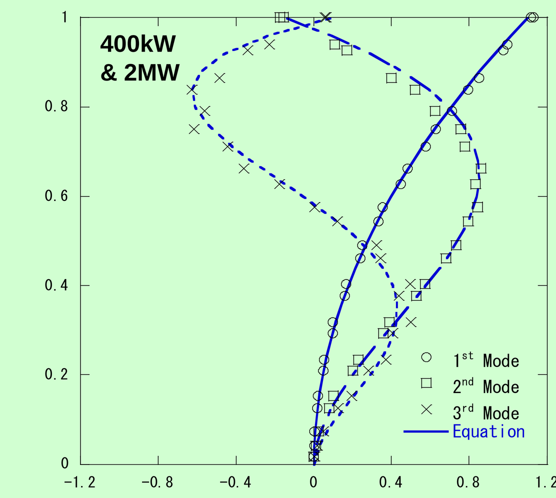


Fig. Model participation function

Significant contribution to the design load by 2nd and 3rd modes is observed for 2MW turbine as shown below. SRSS method is used for superposition of these modes.

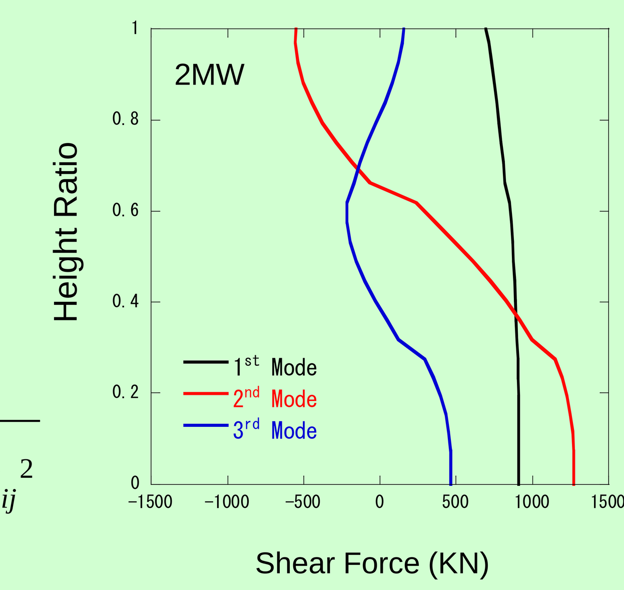
Seismic load for each mode:

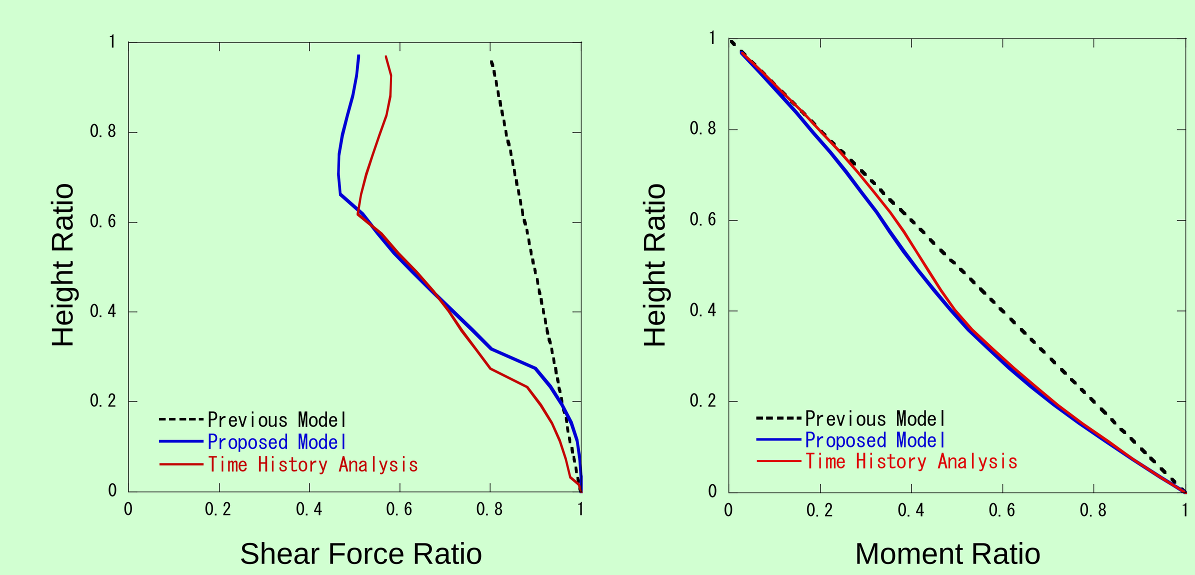
$$Q_{ij} = \sum_{k=i}^{n} F_{kj} = \sum_{k=i}^{n} \gamma_j X_{kj} S_a(T_j, \zeta) m_k$$

$$M_{ij} = \sum_{k=i}^{n} F_{kj}(z_k - z_i)$$

SRSS mode superposition:

$$Q_i = \sqrt{\sum_{j=1}^{n} Q_{ij}^2}, \quad M_i = \sqrt{\sum_{j=1}^{n} M_{ij}^2}$$

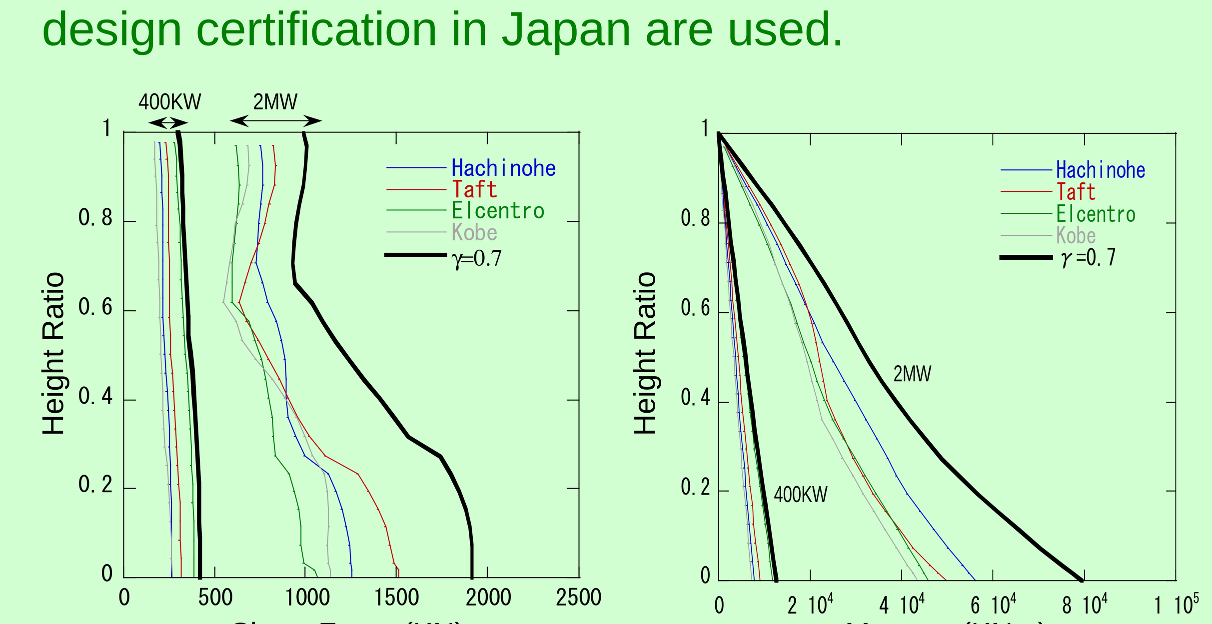




Distribution of calculated load has successfully captured non-linearity of the load profiles obtained by time history analysis.

Determination of γ by Code Calibration Method

To determine suitable quantile (γ) for defining reliable design spectrum, code calibration method[6] is adopted. In this study, seismic waves for obtaining the structural design certification in Japan are used.



A γ-value of 0.7, i.e., 70% quantile, is identified to obtain reliability level similar to that of the current design code.

Conclusions

This study proposes a model for the damping correction factor that accounts for uncertainty in the response spectrum and natural period of wind turbine. In addition, formula for analytical estimation of complex profile of seismic design loads are presented. Finally accuracy of proposed formula is verified against time history analysis and reliability level similar to that of current design code is demonstrated.

References

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