VALIDATION OF SEISMIC-OPERATIONAL LOAD COMBINATION RULES FOR WIND TURBINES IN SUBDUCTION ZONES USING DIRECT TIME-HISTORY MULTIBODY ANALYSIS

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Abstract

The combination of seismic and operational/wind loads that occur concurrent with earthquakes for the design and verification of wind turbine towers and foundations using conventional modal response spectrum analysis procedures requires special consideration due to the highly non-linear nature of the respective loads, and the fact that peak load responses are not correlated in time or direction. While it is possible to perform combined seismic and aeroelastic response history analysis, this approach is not practical where foundation designers and local reviewers other than the turbine designers lack access to proprietary turbine control models or require analysis of separate load states for ASD or LFRD designs/validations. While several works by Prowell, Asareh and others have demonstrated the reasonability of SRSS combination rules, such as those currently incorporated in IEC wind turbine design provisions, for deep and crustal earthquakes, no significant work has yet been performed including records of large subductive earthquakes, where strong motion duration is typically much longer than other strong ground motion events. In this work, a series of time history analyses are carried out using NREL's FAST simulation software and the 5-MW Reference Turbine, using records from the 2010 8.8 Mw Maule subductive earthquake in Chile under different wind conditions. Results are then analyzed in order to verify whether existing addition rules indicated by current American and European standards are still valid in subduction zones, and concludes with a recommended rule for load combination in such subduction zones

Keywords: earthquake engineering; wind turbine; time history; non-linear; multi-dynamics.

1. Introduction

Wind turbines are mass-produced, model-type units that cannot be readily customized for specific sites due to scale economies. For this reason, structural design for their components (including tower, nacelle and blades) is performed for generic loads which are then compared to the applicable site-specific loads. Wind loads are computed for generic class, model-dependent wind speeds, and then validated for the selected site. Combination of wind and earthquake loading can be performed by direct time history analysis, but due to local regulations, including requirements for independent review, it is desirable to at least have the option to establish independent load cases and combine them afterwards. This combination of loads may lend itself to overdesigning, especially in the case of turbine towers and their foundation, since direct addition of peak earthquake and operational/wind loads may overestimate actual load demand from simultaneous occurrence of these events.

While several works by Prowell [7], Asareh [5] and others, as well as the current definition from both IEC [1] and ASCE/AWEA [6] standards recommend the application of SRSS or 75% addition rules for operational wind and earthquake loads, no significant studies have been yet published analyzing the combination rules in the case of large subductive earthquakes, whose longer duration and different frequency content from other types of earthquakes used in the available literature may yield different results when studying simultaneity of peak loading. To address this knowledge gap, this paper presents the results of 300 simulations using multibody dynamic analysis software, incorporating ten earthquake records from an ample geographic area from Chile's 2010 8.8 Mw Maule event, concluding in the recommendation of an adequate addition rule to combine operational wind and earthquake loads in subduction zones.

2. Analysis Approach

Addition rules were validated through a series of combined earthquake and operational/wind load time history simulations that included ten records from the 2010 8.8 Mw Maule earthquake, as well as random turbulent wind loads, considering the four seismic analysis cases defined by IEC [1]: normal operation, emergency stop, idling and parked turbine. A total of 300 simulations were carried out, distributed as follows:

- Normal operation: 10 earthquake records, each one considering 10 random turbulent wind loads at Vr (detailed definition in paragraph 5 below), resulting in 100 simulations. For each simulation (i.e. combination of a single earthquake record and wind time series), analysis was performed for earthquake only, wind only and simultaneous earthquake plus wind.
- Emergency stop: 100 simulations, corresponding to the same combination of earthquake records and turbulent wind time series defined above, but including the activation of the turbine's emergency braking system 15 seconds from the initiation of earthquake loading.
- Idling: 100 simulations as above, considering resting initial conditions and earthquake loading within 30 seconds of turbine rotation ramp up.

For each case, peak load results from individual wind and earthquake cases are combined using different addition rules, and then compared with the directly simulated combined time history result.

3. Software

Simulation was performed using the Seismic module for FAST [2], which expands the multibody dynamics analysis of the original NREL software package by adding the capability of entering earthquake loading as a motion time history at the tower base. It is important to note that an operating turbine is a dynamic system -a mechanism- and thus its behavior cannot be accurately simulated by using traditional structural analysis software because a moving wind turbine is not a set of statically connected parts, but a set of individually flexible components joined by dynamic constraints. Traditional structural software may approximate the analysis for a parked, fully braked turbine, but will not represent the aerodynamic component or the effect of rotation of the blades' mass.

4. Turbine Model Definition

Analysis was performed using the 5-MW NREL Reference Turbine, developed by the National Wind Technology Center (NWTC) [3], which allow results to be based on a widely validated, albeit generic turbine model. Properties for this model are defined in Table 1 below.

Table 1 – Properties of the 5-MW NREL Wind Turbine

Parameter	Value
Rated power	5 MW
Rated wind speed Vr	11.4 m/s
Hub height	90 m
Rotor diameter	126 m
Tower height	87.6 m
Rotor mass	111,000 kg
Nacelle mass	246,000 kg
Tower mass	347,460 kg

5. Wind Loading

Wind turbines are characterized by the rated wind speed Vr, the hub-level speed at which the turbine produces its nominal power. Itis important to note that this parameter is a property of the turbine model and not of the site. Since wind turbines are mass-produced machines, it is not economically feasible to design them for site specific wind velocities, so while the design of wind farms extensively analyzes local conditions, individual turbine design is performed for a general condition, and then selected for the site. Conventional seismic design combines an earthquake load with operational/wind loads determined from the Vr wind speed that is assumed to occur concurrently with the earthquake. The selection of Vr is conservative not only because it tends to impose maximum horizontal thrust loads during turbine operation for common pitch-regulated turbines, but also because it does not typically reflect the most probable wind speed to occur during the design earthquake. The most probable wind speed is approximately the local site mean wind speed, which is nearly always less than Vr and imposes less load on the turbine and support structure. Widely accepted practice assumes a Weibull probability wind speed distribution, which means that when Vr is equal or higher than the site median speed, the probability of occurrence of Vr simultaneously with the design earthquake reduces rapidly. For example, using a Weibull distribution with k = 2, and assuming a local site mean wind speed of 7 m/s (a reasonably typical value), the probability of occurrence of a 11.4 m/s or greater speed (Vr for the reference turbine used in this study) is only 7.1%. If the site mean wind speed is 10 m/s, the probability of occurrence of the studied Vr or greater is 27%. Stochastic wind analysis far exceeds the scope of this paper, but it is plausible to state that if the turbine's Vr is equal or greater than the site mean wind speed, combining the design earthquake and Vr-related wind load is a conservative scenario.

The actual design wind load is a stochastic time series, defined by the Vr reference speed and a turbulence level (stochastic variation around Vr). In this case we used NREL's TurbSim [4] software to generate randomized wind speed time series for each simulation, using the Kaimal turbulence model as well as IEC type C turbulence characteristic. This allows to establish a time series centered around Vr, defining the "shape" (turbulence model) and "size" (characteristic) of the randomness.

6. Earthquake Records

Since the main goal of this study is to validate addition rules for subduction zones, 10 records from the 2010 8.8 Mw Chilean Maule earthquake were used in the simulation. Table 2 below shows the different records and corresponding PGAs. Only a single component was used (not necessarily the one with the record's highest PGA), parallel to the wind, and a 0,1-25 Hz filter was applied. The records were not spectrum matched or scaled in any other way in relation to Chilean code.

Table 2 – Earthquake Records Used in Simulation (2010 8.8 Mw Maule Earthquake)

Record Site	PGA [g]
Angol	0.74
Concepción	0.41
Curicó	0.50
Hualañé	0.40
Llolleo	0.34
Matanzas	0.35
Papudo	0.30
Santiago Centro	0.22
Talca	0.49
Valparaíso Almendral	0.23

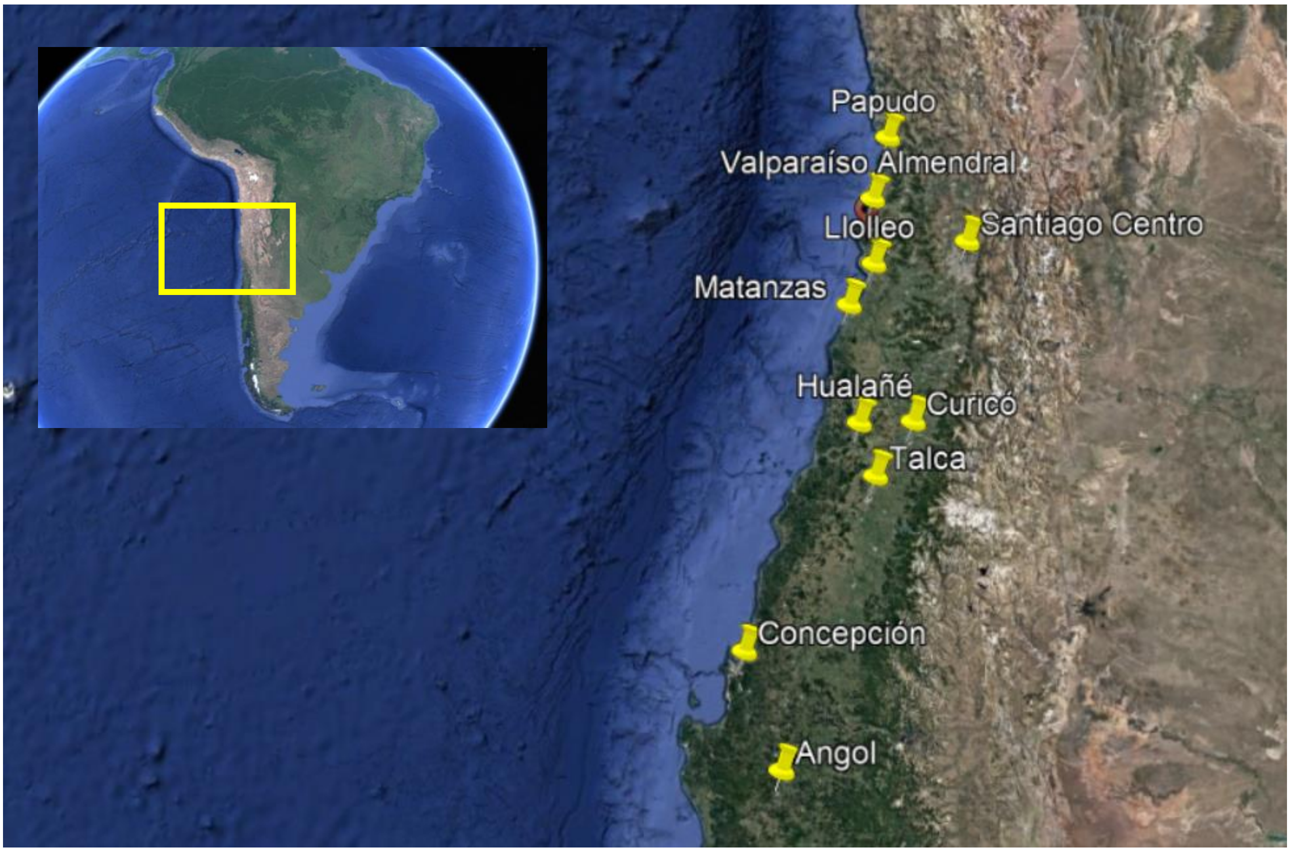

Fig. 1 – Earthquake Record Location Spanning Over 600 km in Central Chile (image source: Google Earth)

7. Analysis Results

In order to analyze results for each simulation, the following non-dimensional parameters were defined:

$$R-75 = \frac{0.75 \cdot (W+E)}{DC} \quad (1)$$

$$R-SRSS = \frac{\sqrt{W^2+E^2}}{DC} \quad (2)$$

$$R-100 = \frac{W+E}{DC} \quad (3)$$

Where:

- W: quantity computed independently for operational/wind load
- E: quantity computed independently for earthquake load
- DC: combined operational/wind and earthquake load quantity computed through time history simulation

The use of these non-dimensional parameters allows to quickly visualize if an addition rule is conservative for a determined result parameter. For example, a R-SRSS value of 1.2 means that independently adding wind and earthquake calculations using the SRSS addition rule yields a value 20% higher than that obtained by combined time history simulation.

For the purposes of this paper, only overturning moment at the tower base was considered for the comparisons, although this can be readily expanded to other parameters or locations within the turbine and its main components.

7.1 Normal Operation

As previously stated, normal operation (earthquake plus Vr-centered random wind) was evaluated for ten earthquake records and ten random wind time series, yielding a total of 100 analysis cases.

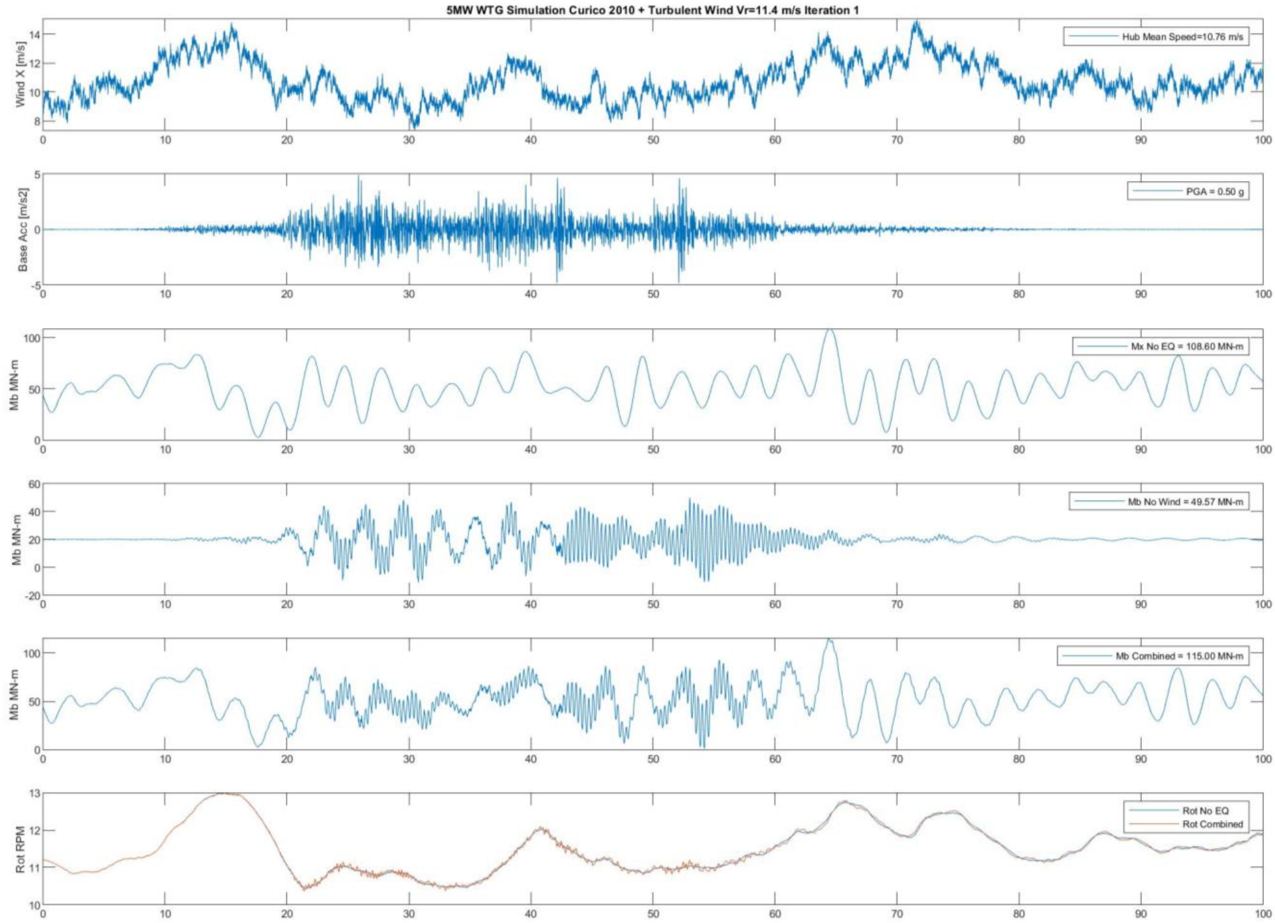

Fig. 2 – Normal Operation Analysis Example (Wind Speed, Ground Acceleration, Base Moments for Wind, Earthquake and Combined Loads, Rotor Angular Speed).

Figure 2 shows the results of one of these simulations, including: random wind speed, input ground acceleration, tower base overturning moments for wind, earthquake and combined cases, as well as the rotor angular velocity, in a window with non-zero initial conditions (for each case, about 300 seconds of analysis were allowed prior to the initiation of ground acceleration in order to stabilize the numerical calculation). Base moment plots for all combined simulations, of which Figure 2 is representative, show that instantaneous variation in wind speed has more incidence in maximum response value than the peak earthquake accelerations, so direct addition of independently computed wind and earthquake response overestimates the superposition of these loads. Table 3 shows statistics for all 100 simulations performed for earthquake plus normal simulations. Per these results, the 0.75·(W + E) addition rules average a 10% higher value than the combined time history analysis, while the SRSS rule yields a slightly lesser value. Direct addition of independently computed peak wind and earthquake loads yields a 46% larger value in comparison to the combined time history load results, that is, a major overestimation of base loads. During normal operation, aerodynamic damping has its maximum value, so response for earthquake load in the combined time history analysis is less than the independent scalar analysis, corresponding to the theoretically expected results.

Table 3 – Addition Rule Analysis for Normal Operation Simulations

Site	**PGA**	**R-75**		**R-SRSS**		**R-100**	
	(g)	**x**	**σ**	**x**	**σ**	**x**	**σ**
Valparaíso Almendral	0.23	1.09	0.08	0.98	0.01	1.46	0.10
Angol	0.74	1.07	0.06	1.00	0.01	1.43	0.07
Concepción	0.41	1.07	0.08	0.94	0.00	1.43	0.11
Curicó	0.50	1.05	0.06	1.01	0.01	1.40	0.07
Hualañé	0.40	1.12	0.09	0.96	0.01	1.49	0.12
Llolleo	0.34	1.09	0.10	0.97	0.01	1.45	0.14
Matanzas	0.35	1.16	0.14	0.95	0.00	1.55	0.19
Papudo	0.30	1.08	0.08	0.97	0.00	1.45	0.10
Santiago Centro	0.22	1.12	0.07	0.97	0.01	1.50	0.09
Talca	0.49	1.12	0.12	0.95	0.00	1.50	0.16
Overall	**NA**	**1.10**	**0.09**	**0.97**	**0.02**	**1.46**	**0.12**

7.2 Emergency Stop

100 cases were also analyzed comparing time history combination with independent peak wind or earthquake loads. Figure 3 shows the results for base overturning moment for one of the 100 studied scenarios, while Table 4 summarizes the statistics for the R-75, R-SRSS and R-100 parameters. In these simulations, the turbine's emergency brakes are activated 15 seconds after the initial part of the earthquake acceleration load. In this example, representative of the other 99 simulations for this scenario, the moments associated with the detention of the turbine (free oscillation) decay with magnitudes comparable to those of the earthquake loads alone. It must be noted that the full detention of the turbine takes about five seconds, which is an overestimation since modern turbines have control systems that allow for a more controlled stop, effectively damping the free oscillation effects. Statistical analysis of the non-dimensional parameters, as shown in Table 4, yields virtually identical results than those obtained for the normal operation simulations. As before, the results demonstrate that wind speed variation is more incident than the combinations of peaks for the independent loads.

Table 4 – Addition Rule Analysis for Emergency Stop Simulations

Site	**PGA**	**R-75**		**R-SRSS**		**R-100**	
	(g)	**x**	**σ**	**x**	**σ**	**x**	**σ**
Valparaíso Almendral	0.23	1.12	0.08	0.98	0.01	1.50	0.11
Angol	0.74	0.99	0.10	0.99	0.02	1.32	0.11
Concepción	0.41	1.07	0.11	0.94	0.00	1.43	0.15
Curicó	0.50	1.04	0.06	1.00	0.01	1.39	0.09
Hualañé	0.40	1.13	0.07	0.96	0.01	1.51	0.09
Llolleo	0.34	0.93	0.13	0.99	0.01	1.24	0.18
Matanzas	0.35	1.22	0.14	0.94	0.00	1.62	0.19
Papudo	0.30	1.12	0.07	0.96	0.01	1.49	0.10
Santiago Centro	0.22	1.21	0.04	0.97	0.01	1.62	0.05
Talca	0.49	1.13	0.13	0.95	0.00	1.51	0.17
Overall	**NA**	**1.10**	**0.13**	**0.97**	**0.02**	**1.46**	**0.17**

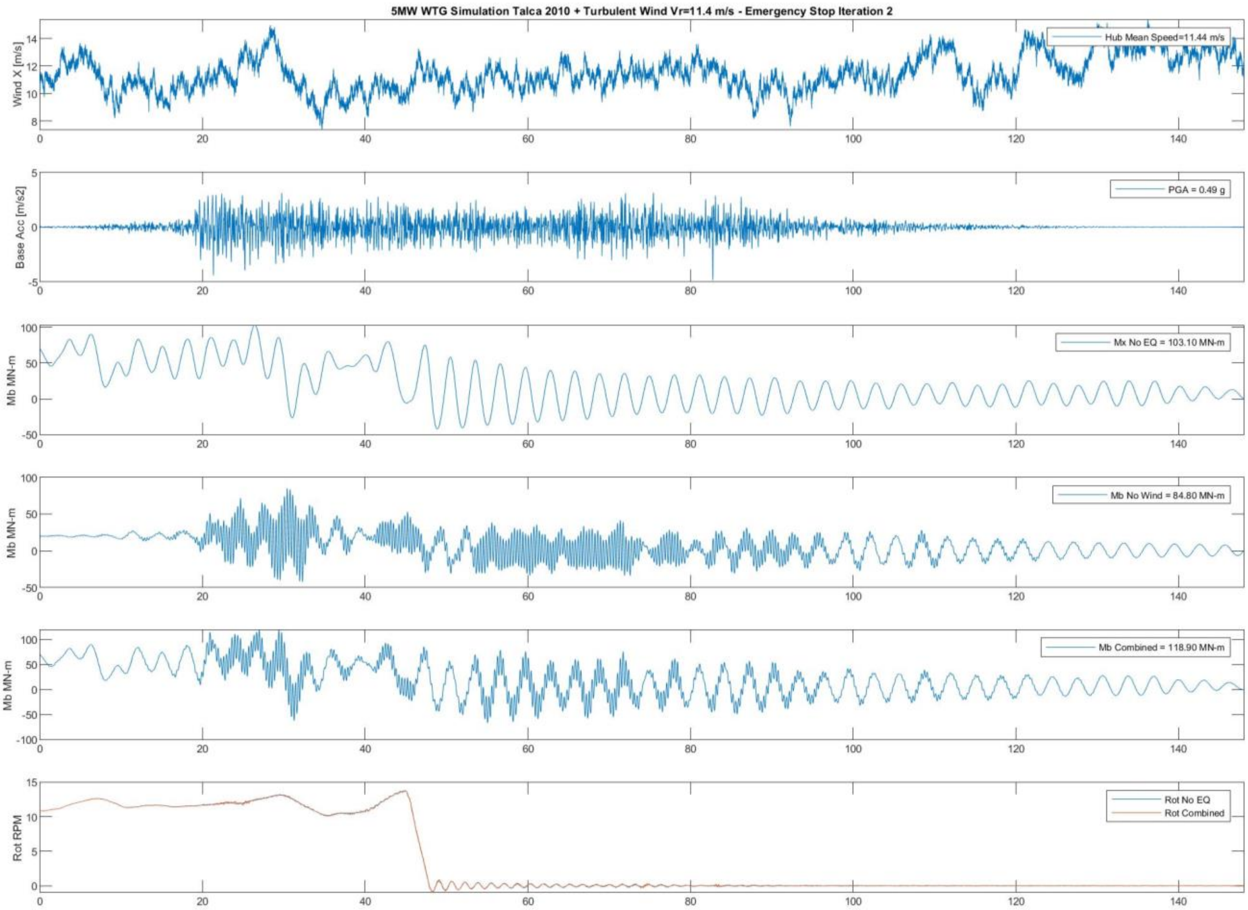

Fig. 3 – Emergency Stop Analysis Example (Wind Speed, Ground Acceleration, Base Moments for Wind, Earthquake and Combined Loads, Rotor Angular Speed).

7.3 Idling

The third analysis case corresponds to the arrival of the earthquake loads in the first 30 seconds of turbine idling. Theoretically, this scenario is relevant because in this stage, transient loads from the turbine startup are at their maximum. However, since wind speed is not constant, local maxima from this load alone are higher as a function of the varying wind load, and not necessarily at the beginning of the operation. Figure 4 shows results for one of the 100 simulations performed for this case, while Table 5 summarizes the statistics for the non-dimensional parameters. These statistics are once again virtually identical to those of the normal operation and emergency stop cases, representing that wind load variation has a higher effect on the overall response than local peak combination from wind and earthquake.

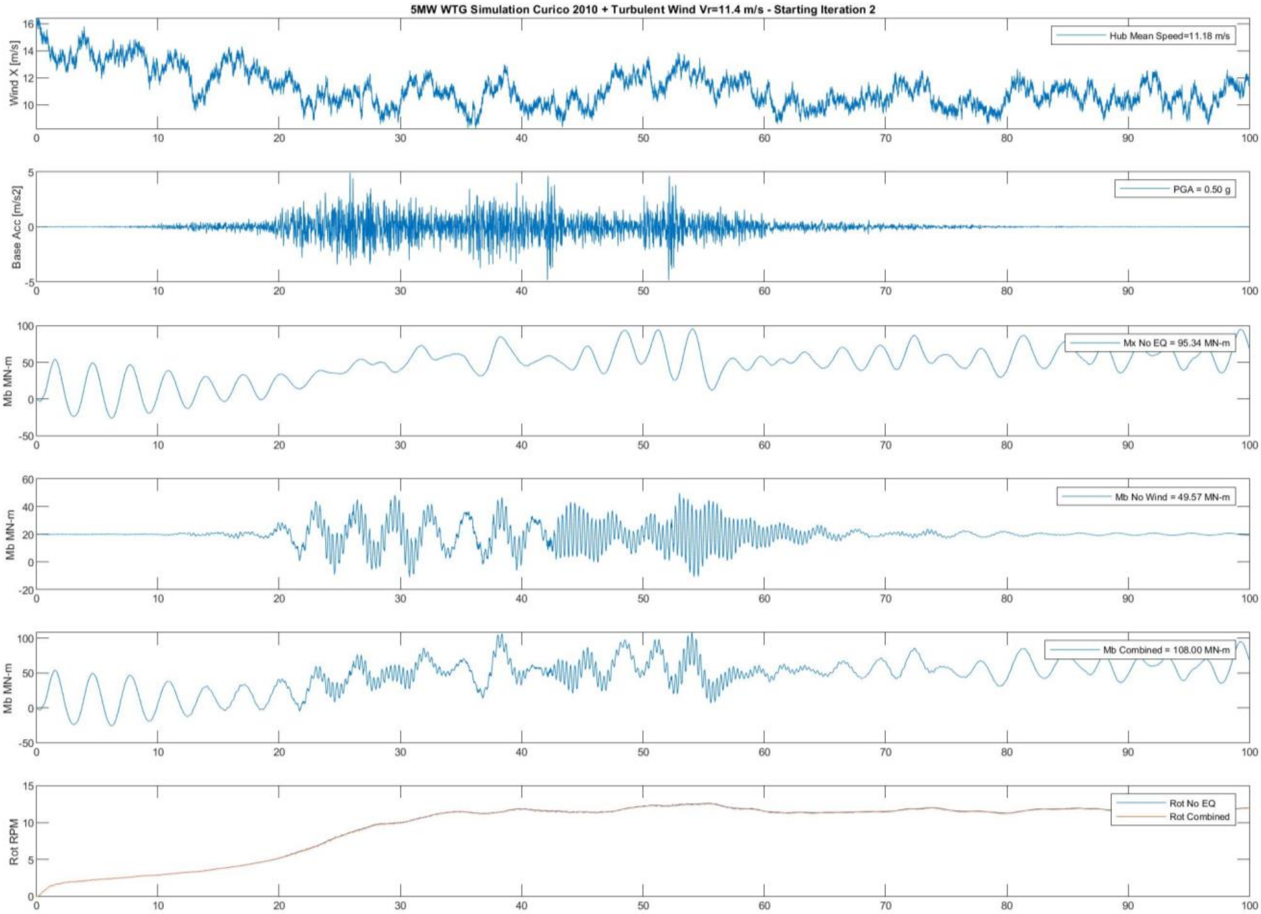

Fig. 4 – Idling Analysis Example (Wind Speed, Ground Acceleration, Base Moments for Wind, Earthquake and Combined Loads, Rotor Angular Speed).

Table 5 – Addition Rule Analysis for Idling Simulations

Site	**PGA**	**R-75**		**R-SRSS**		**R-100**	
	(g)	**x**	**σ**	**x**	**σ**	**x**	**σ**
Valparaíso Almendral	0.23	1.07	0.05	0.98	0.01	1.43	0.07
Angol	0.74	1.08	0.04	1.00	0.01	1.43	0.04
Concepción	0.41	1.27	0.10	0.94	0.00	1.70	0.14
Curicó	0.50	1.05	0.03	1.00	0.01	1.39	0.04
Hualañé	0.40	1.15	0.09	0.96	0.00	1.53	0.12
Llolleo	0.34	1.11	0.09	0.97	0.01	1.48	0.12
Matanzas	0.35	1.16	0.16	0.94	0.00	1.55	0.21
Papudo	0.30	1.09	0.07	0.96	0.01	1.46	0.09
Santiago Centro	0.22	1.13	0.07	0.96	0.01	1.50	0.10
Talca	0.49	1.16	0.10	0.95	0.00	1.55	0.13
Overall	**NA**	**1.13**	**0.10**	**0.97**	**0.02**	**1.50**	**0.14**

8. Summary

Work presented in this paper is summarized as follows:

- Operational/wind loading for combination with earthquakes can appropriately be evaluated at rated speed Vr. If Vr is equal or higher than local mean wind speed, results will be conservative, since loads associated with this value will be smaller than those most likely to occur in combination to earthquake design load. It must be noted that this paper only considers wind cases reasonably likely to occur simultaneously with an earthquake, and they exclude rare high wind storm cases, which are not combined with seismic loads.
- Ten earthquake records were used, from the 2010 8.8 Mw Chilean Maule subduction zone event. These records were not spectrum matched or scaled to meet local code.
- Addition rules were evaluated by comparing inherently-combined time history analysis results with independent calculations for operational/wind and earthquake loads, considering 300 simulations using multibody time history analysis for three cases of earthquake occurrence: normal turbine operation, emergency stop and idling. It must be noted that multibody analysis can represent the actual moving nature of a wind turbine, while the use of typical structural analysis software cannot include the effect of the rotating mass in the response calculation.

9. Conclusions

The following conclusions are derived from the results presented in this paper:

- Comparative results for the three cases are virtually identical, indicating that the 0.75·(W +E) addition rule is slightly conservative (10-13% higher response than the inherently-combined time history analysis results), SRSS rule is slightly non conservative (3% lesser than the inherently-combined time history analysis results), and that direct sum scalar addition of peak wind and earthquake loads results is overly conservative (46-50% higher than the inherently-combined time history analysis results). These results are consistent with those obtained by Asareh [5], who performed a similar analysis using earthquake records from mainly non-subductive earthquakes.
- Peak operational/wind and earthquake responses were evaluated in a single direction, which assumes that wind and seismic loads coincide in both time and direction. This conservative approach likely explains why direct sum additional of peak operational/wind and earthquake loads that was omitted from the addition rule analysis.
- The results from this paper demonstrate that wind turbine seismic load response in subductive earthquakes does not vary significantly from previous studies based on non-subductive events, and that the addition rule proposed by both IEC [1] and ASCE/AWEA [6] are applicable for sites where subductive earthquake mechanisms dominate local seismic hazard.
- It is then recommended that a 0.75·(W + E) addition rule is applied when combined time history results are not available, considering W as the largest response among normal operation, emergency stop and idling wind loads at reference speed Vr, if this value is higher than the local wind speed average.

10. Further Work

The theoretical results presented herein could conceptually be validated through development of a seismic monitoring system for currently installed wind turbines. Most, if not all, commercial turbines already have accelerometers installed in their nacelles, so the implementation of this system via addition of base level instrumentation and signal combination could conceivably be incorporated into existing SCADA infrastructure.

11. References

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