Chapter 2
Damping Ratio Assessment for Two Full-scale Operational Onshore Wind Turbines

T. Nunez and C. E. Ventura

Abstract With the increasing deployment of wind energy projects in highly seismic regions, new codes and recommended practice documents have emerged, such as NCh2369-2023 (Chile) and DNV-RP-0585-2021 (International), both influenced by IEC 61400-1 (2019) and IEC 61400-6 (2020). These documents consider the unique condition where seismic and wind loads are comparable. However, despite the new challenge imposed by this condition, added to a thriving industry that is constantly pushing to increase the size and height of wind turbines, most of the codes establish a value of 1% for a stopped turbine, that is, purely structural damping, and 5% for an operating turbine, a value that accounts for the aerodynamic behaviour associated with the rotation of the blades in a fluid. These values are based on limited literature, such as Prowell et al. [5] or Ishihara [6] for onshore WTG types. Nowadays, commercial turbines operating worldwide typically surpass 5 MW and 140 m hub heights. Hence, the need for continuous calibration of normative damping parameters, a key aspect of our ongoing research, appears evident. Based on the previously stated need, this work presents the experimental determination of the natural frequencies and their respective damping ratios for parked and operational conditions of two full-scales operational onshore WTG located in Chile and Argentina, with 140 mts and 87.6 mts, respectively. New correlations between period and damping ratio, including fore-aft and side-to-side directions, are proposed to update the current recommendation of the IEC61400-6 (Annex P) standard for design values.

Keywords Damping ratio · full-scale wind turbine · structural monitoring · onshore wind turbines

Introduction

Wind energy is one of the most rapidly growing renewable sources worldwide, having an installed capacity of 899 GW by 2022, triple that of a decade ago [1]. Much of this development has occurred in seismic zones, so the study of the structural and seismic design of wind turbines constitutes a key field not only for seismic engineering but also for global decarbonization goals. Although it is possible to use full FEA or multibody models, the most widely used model for preliminary seismic analysis of wind turbines corresponds to the "stick model," which simplifies the system, assuming it as a fixed base tower, with the mass of the equipment and blades lumped at its top and uniformly distributed through the tower, thus ignoring the displacement and flexibility of large components. This simplified model allows for calculating seismic loads using design spectra, readily available in most design codes. To perform this analysis, a proper determination of modal properties of the studied system, namely natural frequencies and damping, is essential to obtain accurate, representative results through the modal spectral method. In the case of damping for wind turbine seismic analysis, the most widely used standards, namely IEC61400 [2] and ASCE-AWEA RP2011 [3], establish a value of β=1% for a parked turbine, that is, purely structural damping, and β=5% for an operating turbine. This value accounts for the aerodynamic behaviour associated with the rotation of the blades in a fluid, in this case, air. These damping values are based on limited literature regarding full-scale tests available at the time of publication of the abovementioned standards, such as Prowell et al. [5], using a 65 KW, laboratory-tested, 21.9-meter hub height wind turbine or Ishihara [6] with a 36-meter hub-height full scales onshore type. Nowadays, commercial turbines operating worldwide typically go over 5 MW and 140 m hub heights. Hence, the need for continuous calibration of normative damping parameters appears evident. This study seeks to examine the results of ambient and operational vibration monitoring for two full-scaled onshore wind turbines located in southern Chile (140 mts hub-height), considered a

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seismic prone area, and Argentina (87.6 mts hub-height), evaluating their natural frequencies (periods) and damping ratios. Complementary, this study intends to validate the design damping ratio values recommended by IEC 61400-6 and propose an update of the current recommendation given in Annex P.

Literature Review

As previously stated, design codes [2, 3] coincide with the recommendations of damping values for the operational and seismic analysis of wind turbines. These codes establish damping ratio values associated with four operational conditions to be analyzed jointly with the earthquake case, as summarized in Table 1 below.

Table 1 Damping Values for seismic design under different operational conditions [2–4]

Operational Condition	Damping Ratio (β)
Standstill	1%
Normal operation, Idling and Emergency Stop	5%

In addition to the recommended design values previously summarized, IEC61400-6 [13], Annex P, presents a guideline for the adjustment of structural damping without aerodynamic effects -that is, only the standstill case- as a function of the first natural period (T1) of a steel tower as follows:

$$\beta\,(\%) = 2.0e^{-1.3\bullet T1} + 0.15 \quad (1)$$

It should be noted that the above expression is validated by different authors, such as Prowell [5], Ishihara [6] and Oh and Ishihara [7], but only calibrated for natural periods up to 2.8 seconds, using only 3 points. Figure 1 shows the plot and correlation derived from the Eq. (1).

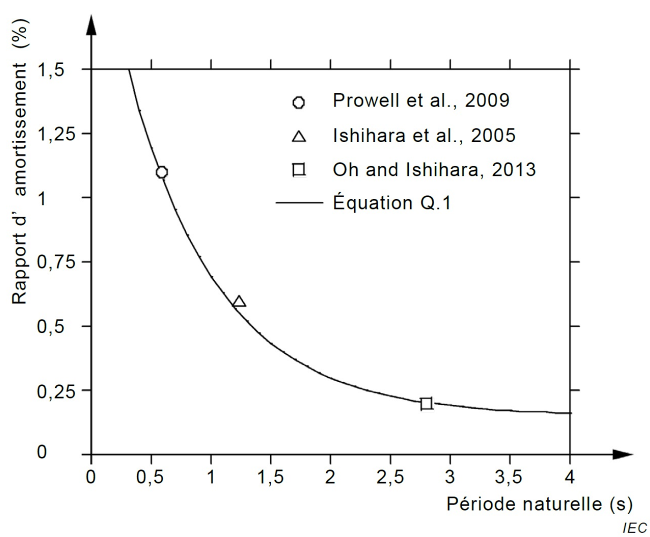

Fig. 1 First mode damping ratio for the steel tower of the wind turbine. IEC 61400-6

Oliveira et al. [11] long-term monitoring research reveals variability in damping ratios, correlating them with wind speed. They find an important increase in fore-aft damping and less impact on side-to-side damping.

Description of the Full-scale Test Case Studies

Case Study 01: 140-meter hub height, 4.5 MW, located in Chile

The test article consists of a commercial 4.5-MW wind turbine generator with a hub height of 140 m, already operational in Southern Chile, one of the most seismic regions in the world. It is worth mentioning that the site is in the rupture zone of two of the largest earthquakes in recent record (Valdivia 1960, Mw=9.5 and Maule 2010, Mw=8.8). Table 2 summarizes this turbine's main relevant design parameters, while Fig. 2 presents some images of the WTG and surroundings.

Table 2 Case Study 01. Wind Turbine Characteristics

Parameter	Value
Nominal power	4.5 MW
Hub height	140 m
Rotor diameter	150 m
Rotor and nacelle weight	210 t
Tower weight	390 t
Tower material	Steel
Tower configuration	5-sections

Fig. 2 Wind turbine generator, located in Chile. General dimensions

Case Study 02: 87.6-meter hub height, 4.5 MW, located in Argentina

The test article consists of a commercial 4.3-MW wind turbine generator with a hub height of 87.6 m, already operational in the province of San Luis, Argentina. Table 3 summarizes this turbine's main relevant design parameters, while Fig. 3 presents some images of the wind turbines and surroundings.

Table 3 Case Study 02. Wind Turbine Characteristics

Parameter	Value
Nominal power	4.5 MW
Hub height	87.6 m
Rotor diameter	150 m
Rotor and nacelle weight	210 t
Tower weight	207.1 t
Tower material	Steel
Tower configuration	3-sections

Fig. 3 Wind turbine generator, located in Argentina. General dimensions

Field Test Setup

Case Study 01: 140-meter hub-height

Experimental testing was performed on-site during a 2-session campaign, comprised of 2-hour standstill and 19-hour operational vibration measurements, including idling, stopping and continuously varying wind speeds, using four high-sensitivity velocity sensors and four acceleration sensors, as detailed in Table 4. Figure 4 shows the configuration for the monitoring plan. Only Trominos sensors were used for dynamic parameter estimation as a preliminary assessment.

Table 4 Vibration Measurement Equipment

Equipment	Quantity	Characteristics
High-sensitivity velocity sensors	4 (one at the tower bottom, one at mid-height and two at the tower top). Triaxial.	Moho Tromino @128 Hz
Acceleration sensors	4 (one at tower bottom, two at middle positions and one at tower top). Triaxial	Endaq S3 @128 Hz

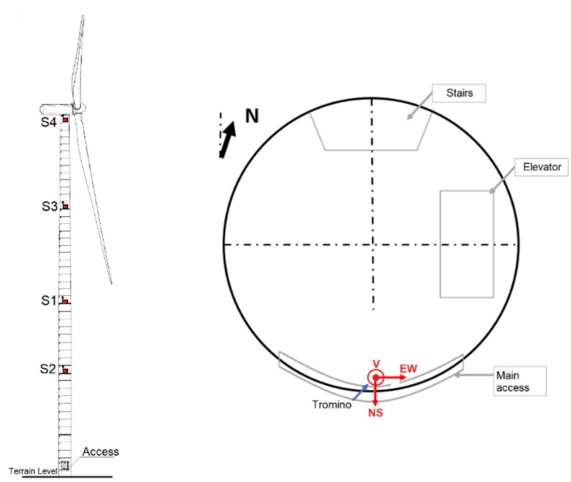

Fig. 4 Monitoring plan (Tromino only). Left: Sensor deployment along the tower. Right: sensor location in plan (typical)

Case Study 02: 87.6-meter hub-height

Experimental testing was performed on-site during a 2-session campaign, comprised of 18-hour operational vibration measurements, including idling, standstill, and continuously varying wind speeds, using four high-sensitivity velocity sensors, as detailed in Table 5. Figure 5 shows the configuration for the monitoring plan.

Table 5 Vibration Measurement Equipment

Equipment	Quantity	Characteristics
Acceleration sensors	3 (two at the tower top and one at the middle position). Triaxial	Endaq S3 @256 Hz

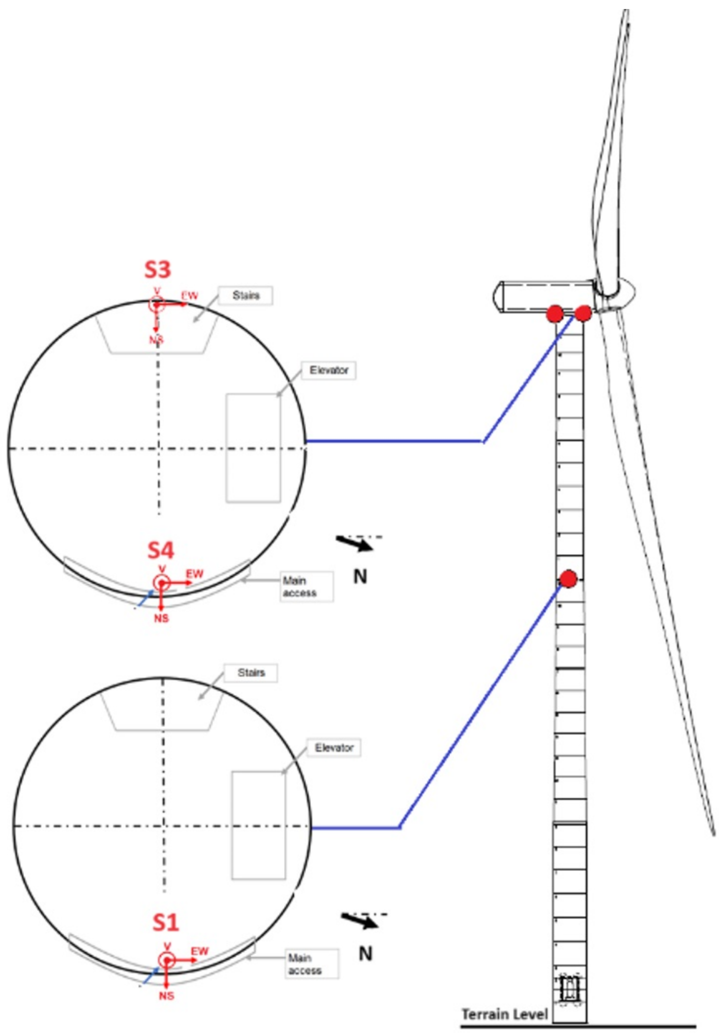

Fig. 5 Monitoring plan (Tromino only). Left: Sensor deployment along the tower. Right: sensor location in plan (typical)

Dynamic Parameters Results

The frequency domain decomposition method and enhanced frequency domain decomposition method were adopted to extract modal frequencies from ambient vibration data. For damping ratio identification, two methods were considered: The half-power method and the Half-quadratic gain method [9].

Parked Condition Results

Table 6 Identified Modal Parameters – Standstill Case. Case Study 01: 140-meter hub height

N°	Frequency [Hz]	Period [s]	β [%]	Direction
1	0.14	6.98	1.25	FORE-AFT
2	0.14	6.98	1.38	SIDE-SIDE
3	0.56	1.79	1.84	SIDE-SIDE
4	0.67	1.49	0.68	FORE-AFT
5	1.08	0.93	0.94	SIDE-SIDE
6	1.16	0.86	0.18	FORE-AFT
7	1.54	0.65	0.39	FORE-AFT

Table 7 Identified Modal Parameters – Standstill Case. Case Study 02: 87.6-meter hub-height

N°	Frequency [Hz]	Period [s]	β [%]	Direction
1	0.23	4.44	0.80	FORE-AFT
2	0.23	4.44	0.94	SIDE-SIDE
3	0.82	1.22	0.35	COUPLED
4	0.88	1.14	1.02	COUPLED
5	2.16	0.46	0.39	COUPLED
6	2.25	0.44	1.11	COUPLED
7	3.16	0.32	0.79	SIDE-SIDE

Operational Condition Results

Operational conditions is only reported for the 140-meter-high WTG located in Chile. Once the initial standstill measurement was completed, a 19-hour measurement was performed with the turbine under normal operational conditions, which included various idling, stopping, and varying wind speed/rotor angular velocity conditions. Operational data, such as average ambient windspeed and rotor angular velocity, were obtained from the turbine's SCADA[1] system, Fig. 6 provides relevant information to correlate with the modal parameters, mainly associated with variations in the wind turbines' damping ratio.

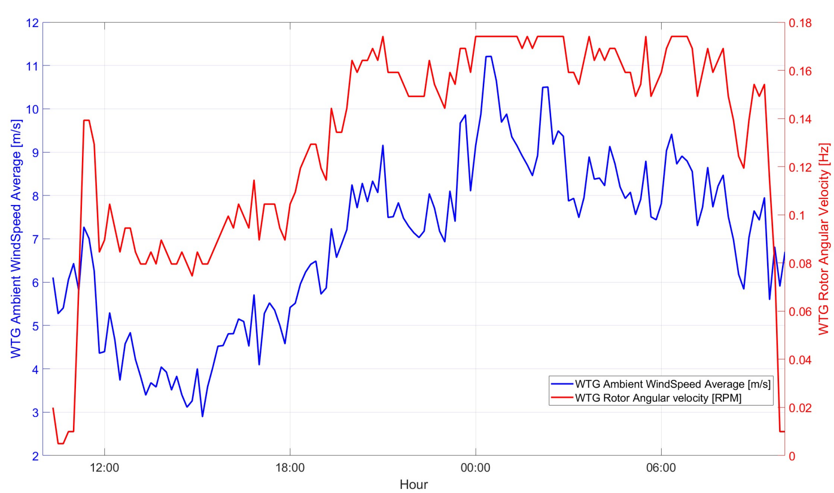

Fig. 6 WTG ambient wind speed average and rotor angular velocity. Case Study 01: 140 mts hub-height

[1] Supervisory Control and Data Acquisition

Considering the duration of the monitoring and the combination of natural and operational frequencies given by the rotor-blades system, the use of the variation of frequency over time constitutes a useful tool to visualize variations in frequency values, as well as closer frequencies during transient periods. In this case, a spectrogram is presented in Fig. 7 to evaluate frequency behaviour and interaction between frequencies over time.

From Figs. 6 and 7, the rotor angular frequency variation reported by the SCADA system coincides with the spectrogram in terms of the variation form. However, the spectrogram presents all the variations amplified by a factor of 3, typically called 3P, associated with three-per-revolution frequency, considering the WTG has three blades. Additionally, the operational 1P frequency seems to be close to the first and second natural frequency of the WTG (fore-aft and side-to-side, first bending). However, most wind turbines work in a range of 1P (or 3P) value, with complex control systems to monitor and bypass resonance effects, e.g., by adding a notch filter to prevent the rotor from resonating at a structural natural frequency for an extended period.

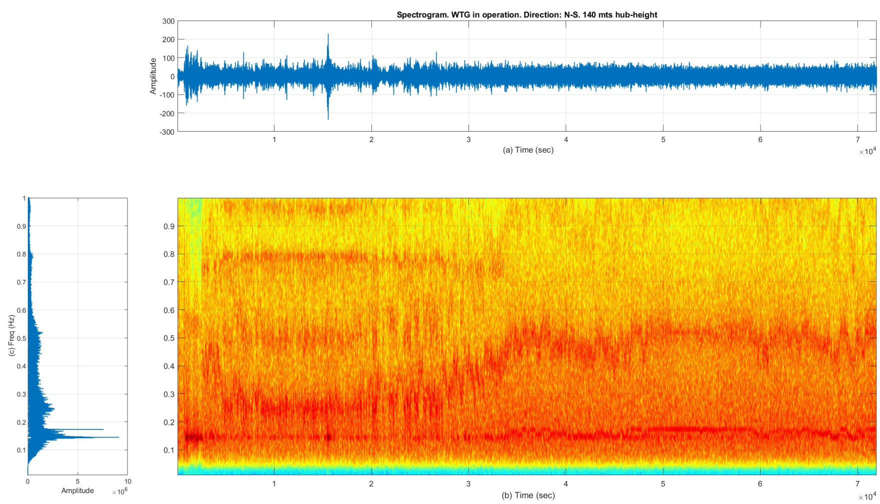

Fig. 7 Spectrogram for 19-hour operational conditions. E-W component (fore-aft.). Case Study 140 meters hub-height. Chile

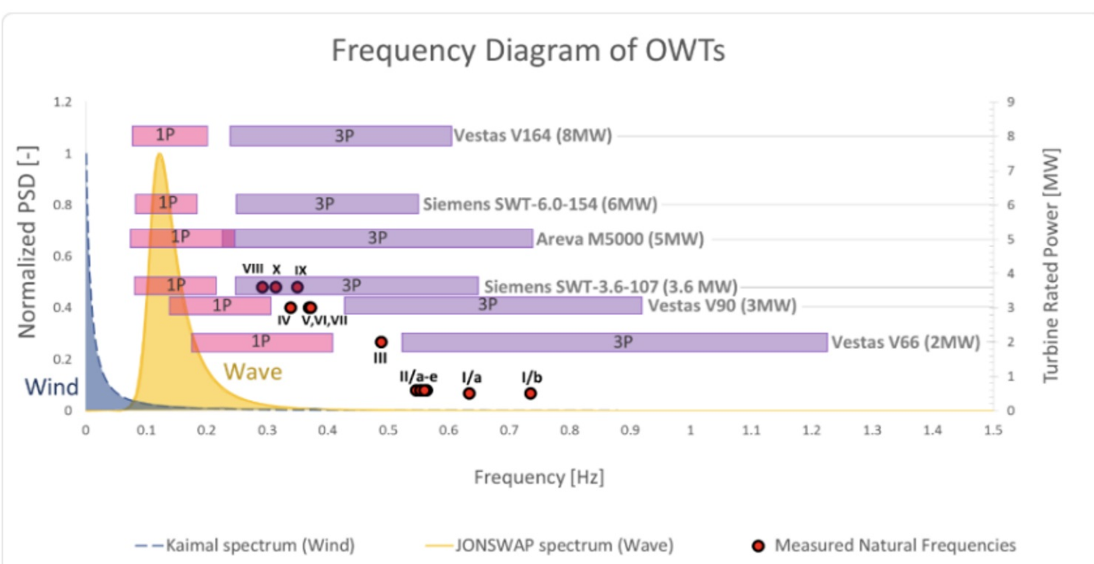

Fig. 8 Typical wind and wave spectra, rotational speed (1P) and blade passing (3P) frequency bands for commercial turbines and measured natural frequencies of the WTG [14]

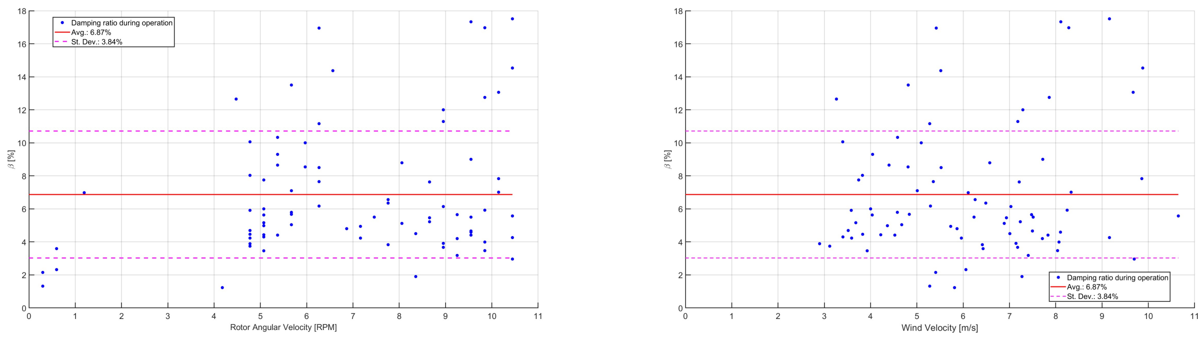

Fig. 9 (a) Damping ratio for operational condition for different (left) rotor angular velocity and (rigth) wind velocity. Only the first bending fore-aft mode is presented

Given the proximity between the operational and natural frequencies of the system, assessing operational damping using the methodologies outlined in this study proves to be complex. Nonetheless, judiciously selecting bandpass filters makes it feasible to isolate the frequency and compute damping across various wind speeds and/or turbine rotor angular frequencies. Figure 9 represents the scattered damping ratio for different wind speeds and rotor angular velocities, aiming to discern any correlation or trend. Each point was obtained for a 30-minute time series processed in the frequency domain and filtered close to the first bending fore-aft mode to obtain the operational damping ratio using the methodologies presented in this article.

From the previous figure, it is unclear whether a trend correlating the increase or decrease in damping with the increase in wind speed or rotor angular velocity can be discerned. However, the results confirm that using a 5% value for operational damping is reasonable. From the figure, an average damping value of 6.87% is obtained, with a standard deviation of σ=3.84%. It should be noted that to obtain a better estimation, some of the following actions are required: (a) longer monitoring periods to increase the sample size, with the additional benefit of generating a structural health monitoring system, and (b) more complex and effective methodologies for extracting operational damping ratios by separating natural frequencies, such as the Hilbert-Huang Transform (HHT) or the wavelet method.

Conclusion

From the analyses of the ambient vibration tests, it was possible to determine frequencies and damping ratios values indistinctly using velocity (Trominos) and acceleration (Endaq) measurements. This is mainly due to the wind conditions that excite the WTG over the noise level of the instruments, especially for acceleration measurements (less sensitive than the velocity measurements).

Using the damping ratios obtained from the standstill measurements and the literature review, it is possible to validate a damping design parameter for parked conditions. Although, it is recognized that there is a certain dependency of the period (and therefore, the mass and stiffness) of the system.

This study shows that currently recommended damping values, such as recommended in Annex P of IEC 61400-6 must be reviewed. Furthermore, the equation presented in that standard does not define the directionality of the natural period, typically known as fore-aft and side-to-side.

In addition, while the value indicated by Prowell [10] is accurate, it corresponds to a scale model developed for laboratory testing. The Ishihara [6] value used for the damping ratio presented in Fig. 1 is for side-to-side mode; however, the value for the fore-aft damping ratio is 1%. Lastly, the value of the damping ratio presented by Oh and Ishihara [7] was obtained from an offshore wind turbine with a tuned-mass damper inside the tower. This particular case cannot be directly compared with an onshore configuration.

It should be noted also that the equation proposed in Annex P of IEC 61400-6, tends to $\beta = 0.15\%$ for longer periods (over 4 seconds), and the value obtained from this study differs significantly from the results obtained from full-scaled WTG monitoring.

It is, therefore, reasonable to propose an updated formula for the damping estimation using the results from this and previous studies, such as those by Ishihara [6] and Oliveira [11]. The following Tables present the damping rations for different periods, for on-shore, steel-tower and distinguishing between fore-aft and side-to-side damping ratio:

Table 8 First Mode fore-aft direction damping ratio (β) comparison from different authors

N°	Author / (Publication Year)	Hub-Height [m]	Rotor Diameter [m]	Natural Frequency [Hz]	Period [s]	β [%]
1	Ishihara (2005)	36.0	31.0	0.81	1.23	1.00%
2	Oliveira et. al. (2018)	76.0	82.0	0.35	2.84	0.68%
3	This Study (2024)	87.6	150.0	0.22	4.55	0.80%
4	This Study (2024)	140.0	150.0	0.14	7.14	1.25%
				Average		0.93%
				Std. Dev.		0.25%

Table 9 First Mode side-side direction damping ratio (β) comparison from different authors

N°	Author / (Publication Year)	Hub-Height [m]	Rotor Diameter [m]	Natural Frequency [Hz]	Period [s]	β [%]
1	Ishihara (2005)	36	31	0.81	1.23	0.60%
2	Oliveira et. al. (2018)	76	82	0.35	2.83	0.80%
3	This Study (2024)	87.6	150	0.22	4.55	0.94%
4	This Study (2024)	140	150	0.14	7.14	1.38%
				Average		0.93%
				Std. Dev.		0.33%

As observed from Tables 8 and 9, it seems reasonable to establish a correlation between the natural period and the damping ratio, updating the equation presented in Annex P of IEC 41600-6. Graphically, Figs. 8 and 9 display the table results, with the average value and its corresponding standard deviation.

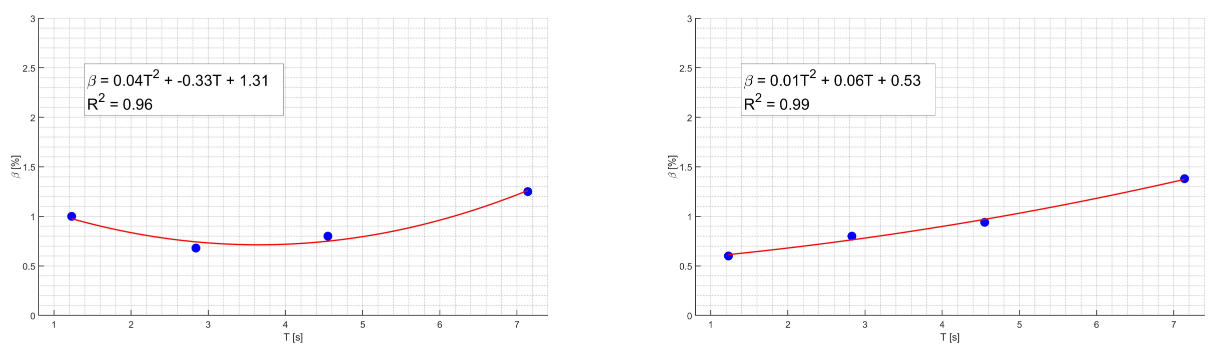

Fig. 10 Proposed relation between damping ratio as a function of the first bending fore-aft natural period (left) and side-to-side natural period (right)

These correlations are subject to change as more towers are assessed, reflecting the evolving landscape of the wind energy market characterized by taller towers and increased power outputs.

Regarding operational vibration measurements, it was not clear to correlate directly the results obtained for the damping ratio with the rotor's angular velocity or wind velocity provided by WTG's SCADA. Despite this fact, the values obtained have an acceptable mean value of 6.78%, close to the design value of 5% proposed by most of the design standards.

The study revealed the difficulties associated with identifying modal parameters when operational frequencies are inherent to the equipment that are also close to the natural frequencies. This is mainly due to the coupling of frequencies, which does not allow for precise damping estimation using the methods employed in this work (half power). From this perspective, it is necessary to explore more complex techniques, such as the Hilbert-Huang Transform (HHT) and wavelet analysis. Additionally, this type of study paves the way for developing continuous monitoring systems, whether operational or seismic.

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References

1. IRENA (2023), Renewable energy statistics 2023, International Renewable Energy Agency, Abu Dhabi.
2. International Electrotechnical Commission (2019). IEC 61400-1 Edition 4 Wind Energy Generation Systems. Part 1: Design Requirements.
3. ASCE-AWEA (2011).RP2011 Recommended Practice for Compliance of Large Land-based Wind Turbine Support Structures, American Society of Civil Engineers-
4. INN (2003). NCh.2369 Of.2003. Diseño Sísmico de Estructuras e Instalaciones Industriales, Instituto Nacional de Normalización.
5. Prowell, I., Veletsos, M., and Elgamal, A., (2008). "Full Scale Testing for Investigation of Wind Turbine Seismic Response." Proceedings of the 7th World Wind Energy Conference, Kingston, Ontario, Canada.
6. Ishihara, T., Phuc, P. V., Fujino,Y., Takahara, K., Mekaru, T.(2005), A Field Test and Full Dynamic Simulation on a Stall Regulated Wind Turbine, Proceedings of APCWE VI, p.599-612.
7. Oh, S., Ishihara, T. (2018), Structural parameter identification of a 2.4MW bottom Fixed wind turbine by excitation test using an active mass damper, Wind Energy, 21(11), 1232-1238.
8. Knudsen, T., Bak, T., & Tabatabaeipour, S. (2012). Detection of excessive wind turbine tower oscillations fore-aft and sideways. 2012 American Control Conference (ACC), 5795-5800.
9. Casiano, M.J. (2016). Extracting Damping Ratio from Dynamic Data and Numerical Solutions.
10. Prowell, I. (2011). An experimental and numerical study of wind turbine seismic behavior. UC San Diego. ProQuest ID: Prowell_ucsd_0033D_11508. Merritt ID: ark:/20775/bb9660041c. Retrieved from https://escholarship.org/uc/item/82b829mg
11. Gustavo Oliveira, Filipe Magalhães, Álvaro Cunha, Elsa Caetano (2018). Continuous dynamic monitoring of an onshore wind turbine, Engineering Structures, Volume 164, Pages 22-39, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2018.02.030.
12. IEC 61400-6 Edition 1 2020-04. Wind Energy Generation Systems. Part 6: Tower and Foundation Design Requirements., International Electrotechnical Commission., 2020.
13. DNVGL-RP-0585. Seismic Design of Wind Power Plants. DNV-GL Recommended Practice, DNV-GL, 2021.
14. Arany, Laszlo & Bhattacharya, Subhamoy & Macdonald, John & Hogan, Stephen. (2016). Closed-form solution of Eigen frequency of monopile supported offshore wind turbines in deeper waters incorporating stiffness of substructure and SSI. Soil Dynamics and Earthquake Engineering. 83. 10.1016/j.soildyn.2015.12.011.