

# Structural performance of an HSFD for mitigating wind turbine tower demand under multiple wind load scenarios

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(Received January 2, 2025, Revised April 27, 2025, Accepted August 5, 2025)

**Abstract.** Large wind turbines face significant challenges in terms of structural stress due to wind loads. Such severe demand, if not properly managed, can reduce the turbine's service life and/or increase its maintenance costs. In this context, the present study focuses on the validation of a passive vibration control device, the Hinge-Spring-Friction Device (HSFD), designed to reduce the bending moment at the base of the tower against wind loads, thereby mitigating structural loads during turbine operation. The HSFD combines a spherical hinge, springs to provide rotational stiffness, and a friction system that dissipates energy through a rocking mechanism. This approach makes it possible to reduce the bending moment at the base of the tower without compromising the overall stability of the structure. In previous work, the design of the device was carried out by the authors considering two reference wind scenarios. Herein extensive validation is performed, against a wide series of operational scenarios representing different wind conditions. The numerical simulations presented in this study cover 91 wind load cases, divided over 13 wind speed ranges, according to IEC 64100-1. These include moderate, intermediate and extreme situations, even close to the turbine cut-out speed (25 m/s), when the turbine stops operating to avoid structural damage. The analyses provided a comprehensive overview of the control system's capacity, enabling the formulation of highly encouraging conclusions. Specifically, the device consistently enhances the system's performance, with the level of protection increasing as the demand for stress rises, achieving an average reduction of approximately 20%.

**Keywords:** wind turbines; vibration control; hinge-spring-friction device (HSFD); device; moment base demand

## 1. Introduction

Wind turbines are advanced structures made from lightweight, high-strength materials, designed to maximize energy efficiency. However, this lightness, combined with their structural flexibility and limited damping, makes them vulnerable to dynamic excitations caused by wind and wave loads, to which they are constantly exposed throughout their lifecycle. Moreover, many wind farms are in seismically active regions, where earthquakes pose an additional source of significant vibrations (Xie and Aly 2020). If not properly controlled, these vibrations, potentially caused by wind, waves and earthquakes can hinder the optimal conversion of wind energy into electricity, accelerate fatigue damage of structural components, and, in extreme cases, even lead to the catastrophic collapse of the turbine (Chou *et al.* 2019).

Mitigating vibrations is therefore crucial to ensuring the structural safety of wind turbines and maintaining their long-term operability. In recent years, research in this field has intensified, aiming to develop effective control strategies to reduce the impact of vibrations. Various control approaches have been proposed in the literature, supported

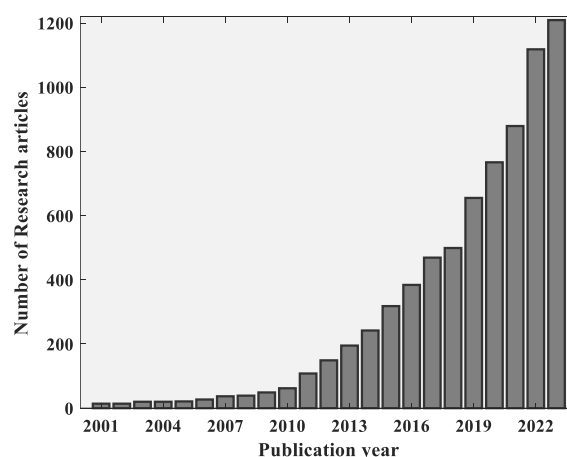


Fig. 1 Scientific production trend about structural vibration control in wind turbines, according to Sciencedirect

by numerical, experimental, and analytical studies that have explored the effectiveness of these methods under different operating conditions.

As shown in Fig 1, the number of scientific publications related to the topic, as recorded by the ScienceDirect database, has increased exponentially over the past twenty years, highlighting the growing interest of the scientific community.

In the context of vibration control in wind turbines,

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Table 1 State of the art about passive control devices for wind turbines. MW= generated power of the case study turbine. Sim=simulation: N= Numerical, E= Experimental

Year	Authors	MW	Device	Sim	Goal
1996	Enevoldsen and Mørk	0.5	TMD	N	Vibration mitigation under fatigue and extreme load
2008	Murtagh <i>et al.</i>	-	TMD	N	Vibration mitigation due to the long-wind force
2009	Colwell and Basu	-	TLCD	N	Peak response reduction
2012	Shadman and Akbarpour	5	TLCD	N	Fatigue load reduction
2012	Li <i>et al.</i>	3.3	BVA	N-E	Reduce nacelle sway displacement and spar roll
2013	Stewart and Lackner	5	TMD	N	Fatigue and ultimate load reductions
2013	Chen and Georgakis	3	STLD	N-E	Increase the damping ratio of the two lowest WT modes
2014	He <i>et al.</i>	5	TMD	N	Control of lateral tower vibrations
2015	Guimarães <i>et al.</i>	5	TMD	N	Reduction of tower vibration under seismic load
2016	Bargi <i>et al.</i>	5	TLCGD	N	Reduction of base moment and top displacement
2016	Zhang <i>et al.</i>	2-3	TLD	N-E	Structural vibration control
2017	Hussan <i>et al.</i>	5	MTMD	N	Response control of offshore jacket platforms for earthquake
2018	Coudurier <i>et al.</i>	5	TLMCD	N	Structural vibration control
2019	Zhao <i>et al.</i>	1.5	VD-SJB	N	Suppressing of tower vibrations under wind and earthquakes
2019	Zuo <i>et al.</i>	5	MTMD	N	Structural vibration control against wind, wave ground motions
2020	Xie <i>et al.</i>	5	STMD MTMD	N	Reduction of tower vibration
2020	Zhang and Fitzgerald	5	TMDI	N	Suppressing edgewise vibrations of blades
2021	Di Paolo <i>et al.</i>	5	RFD	N	Reducing stresses on the tower
2022	Chen <i>et al.</i>	5	TLCD	N	Reduction of blades edgewise vibration
2022	Ding <i>et al.</i>	5	TTLCD	N	Structural vibration control
2023	Rohollah and Tombari	0.06	RCS	N-E	Tower base reinforcement
2023	Wang <i>et al.</i>	4.5	TRCD	N	Structural vibration control
2024	Sorge <i>et al.</i>	5	HSFD	N	Reduction of tower peak moment and fatigue damage
2024	Colherinhas <i>et al.</i>	5	PTMD	N	Reduction of tower vibration
2024	Wu <i>et al.</i>	10	TMD	N	Structural ice-induced vibration control

mitigation technologies can be classified into different categories according to the type of device used and the structural element they are intended to protect (Zuo *et al.* 2020). There are active, passive and semi-active devices, each with specific operating modes. Active devices can dynamically adapt to operating conditions via sensors and actuators and require an external power supply to operate. Semi-active devices, on the other hand, combine passive elements with limited and less energy consuming adjustment capabilities, while passive devices do not require external power and use mechanisms such as dampers or inertial masses to reduce vibration in a simple and reliable manner. These devices can be designed to reduce vibration from different parts of the wind turbine. Some are designed to reduce tower vibration, while others focus on the rotor blades. Passive devices have been widely studied for their effectiveness and ease of implementation in controlling structural vibrations, especially in wind turbine towers, which are subject to cyclic loads generated by the wind and interaction with the rotor itself.

Following the pioneering work of Enevoldsen and Mørk

(1996), who introduced the installation of a Tuned Mass Damper (TMD) at the hub to reduce tower loads, numerous researchers have proposed a wide range of passive control devices. Table 1 summarizes a selection of research papers that explore various types of passive devices for vibration control and wind turbine protection, each with specific objectives. The papers are classified by year of publication, thus facilitating the identification of temporal trends and the evolution of technological solutions over time. Additionally, the rated power of the tower analyzed in the case study is indicated, providing insight into the scale of the turbines and allowing for an evaluation of the potential applicability of the devices to turbines of different capacities. The table also includes the acronym of the passive device used and the specific goal of each study.

Following the above work of Enevoldsen and Mørk (1996), Murtagh *et al.* (2008) proposed the installation of a TMD in the nacelle to mitigate wind-induced vibrations on the tower. The paper shows a significant reduction in vibrations at the top of the tower at different rotor speeds.

Stewart and Lackner (2013) optimized the

characteristics of a TMD with the aim of reducing fatigue loads on both the turbine and the offshore platform. Their results indicate a 10% decrease in fatigue damage for certain device configurations.

Optimization of TMDs did not stop at this initial result. Subsequent studies have explored further possibilities to improve the performance of these devices in vibration control. One area of particular interest is the control of lateral tower displacements, a common problem in wind turbines due to their high structural flexibility. He *et al.* (2014) conducted extensive research on the potential of TMDs to attenuate lateral displacements, showing that these devices can significantly contribute to tower stability under complex dynamic loads. Similarly, Guimarães *et al.* (2015) studied the effectiveness of TMDs in mitigating vibrations induced by seismic events, a problem of growing interest especially for wind turbines installed in earthquake-prone areas. A further area of research concerns the use of TMDs to control vibrations that occur after ice has formed on turbine blades (Wu *et al.* 2024). Ice significantly alters the aerodynamic behavior of the blades, causing imbalances and additional stresses on the tower and the entire structure.

In addition to traditional TMDs, Colherinhas *et al.* (2024) proposed the use of the Pendulum Tuned Mass Damper (PTMD) for controlling typhoon-induced vibrations.

To effectively control the tower vibrations under simultaneous actions of wind, wave and earthquake, Zuo *et al.* (2019) proposed installing multiple TMDs (MTMDs) along the tower to mitigate the first and second vibration modes.

Alongside TMDs, Tuned Liquid Damper (TLD) has also gained attention as an effective solution for vibration mitigation. The most common variants of this device include the Tuned Liquid Column Damper (TLCD) and the Tuned Liquid Gas Column Damper (TLGCD), which differ in the type of fluid used and how the liquid moves within the device.

Colwell and Basu (2009) were the first to predict installing a TLCD on an offshore wind turbine, showing a significant reduction in the turbine's peak response under the combined action of wind and waves. Subsequently, other studies, such as that of Shadman and Akbarpour (2012), confirmed the ability of these devices not only to reduce peak response, but also to decrease fatigue damage accumulated over time.

Zhang *et al.* (2016) conducted an interesting experimental study on the effectiveness of a full-scale TLD tested as a physical substructure in combination with two wind turbines of 2 and 3 MW. Using a 13-degree-of-freedom aeroelastic model, the study showed that TLDs can be a practical and effective solution for vibration control in large-scale wind turbines.

In addition to the traditional TMD and TLD, other control devices have also been developed to mitigate over-vibration in wind turbines.

Li *et al.* (2012) propose an innovative solution for vibration control in offshore wind turbines, using a Ball Vibration Absorber (BVA). BVA consists of a steel ball, an arc path and two steel plates that limit the movement of the

ball. A composite bearing is placed on the arc path to increase friction during ball movement. Energy is dissipated by the rotary motion of the ball and the friction between the ball and the bearing. The authors conducted a series of experiments on a 1/13 scale model of a 3.3 MW wind turbine, subject to different types of stress, including combined wind and wave loads and seismic excitation. The tests demonstrated reduced displacement at the hub, acceleration and stress at the base of the tower and on the platform. However, it should be noted that the BVA is a unidirectional control device and can only control the tower's vibration in one direction. To overcome this problem, Chen and Georgakis, (2013) proposed the use of a tuned rolling damper. In this rolling damper, steel balls in a spherical container can roll freely against the tower vibration, which thus has good vibration control performance in any direction.

Zhao *et al.* (2019) develop a scissor-jack braced viscous damper system (VD-SJB) to reduce structural vibrations of wind turbine towers under seismic and wind loads. The VD-SJB utilizes a geometric amplification mechanism, allowing the displacement of the damper to be magnified, while reducing the damping force required to achieve the same effect compared to a system without a scissor-jack braced arm. The results indicate that the VD-SJB system is effective in reducing turbine tower vibrations under wind and earthquake loads. Optimization of the device parameters was performed using a multi-objective genetic algorithm and a surrogate model based on neural networks.

Rostami and Tombari (2023) propose a device called Reduced Column Section (RCS) for the seismic protection of wind turbines. The main device is a reduced column section, designed as a transition piece between the tower and the wind turbine foundation, characterized by an hourglass shape and made of high-strength steel. The results obtained show that the RCS can effectively reduce stress on the tower wall, enabling a significant reduction in dynamic vibrations. In addition, the RCS makes it possible to increase the fundamental period of the turbine and concentrate the highest stress on a controlled section, thus preserving the main structure.

Di Paolo *et al.* (2021) introduce a passive control technique based on the use of a device called Rotational Friction Damper (RFD), designed to reduce structural stresses in wind turbines induced by wind. Among the objectives is the reduction of bending moment at the base of the tower to limit the stress on the foundation. Simulation on a 5 MW NREL turbine has shown that the proposed system can reduce the moment at the base of the tower by up to 40% in extreme wind conditions when the turbine is parked. After such work Sorge *et al.* (2024) propose the development and optimization of a passive device, called the Hinge-Spring-Friction Device (HSFD), aimed at improving the structural response of onshore wind turbines under wind loads. The device is designed to reduce the bending moments and fatigue damage at the base of the towers, thereby extending the service life of the structures and enhancing their reliability. The proposed case study simulates the behavior of the HSFD system under two different wind scenarios, optimizing the device parameters

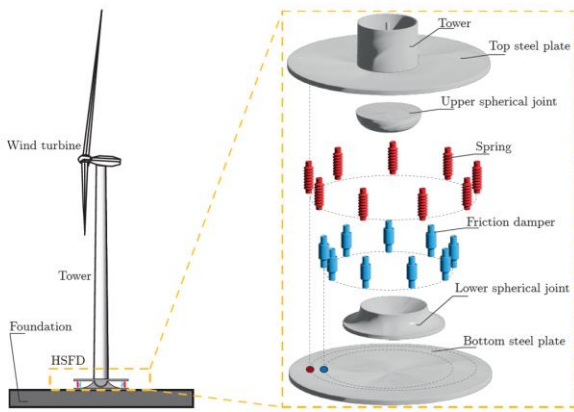


Fig. 2 Possible realization of a 5MW NREL equipped with the HSFD (Sorge *et al.* 2024)

through a multi-objective optimization procedure. The results show that the HSFD significantly reduces both the peak moments at the base and fatigue damage. However, the study is limited in terms of the number of wind load cases considered for design and performance evaluation. Therefore, the objective of this work is to expand the analysis, by further studying the behavior and performance of the HSFD across a wider range of wind conditions, to assess its effectiveness in various operational scenarios and validate the design of the device.

Section 2 describes the components and operation of the HSFD. Then the dynamic model of the case-study 5 MW NREL wind turbine is discussed, finally showing the way to optimally design the device, focused on reducing the bending moment at the base of the tower and mitigating fatigue damage. Section 3 is dedicated to the validation of the HSFD device. The methodology used to simulate the different operational conditions of the turbine is illustrated, with particular attention to the range of wind loads analyzed. The results coming from the controlled structure are compared with the configuration without the device (fixed base), demonstrating the effectiveness of the device in reducing the bending moment at the base of the tower. In Section 4, the results obtained are discussed in detail and highlight the potential economic and operational benefits achievable using the HSFD. Finally, in Section 5 the main conclusions are drawn, together with possible future developments.

## 2. HSFD for passive vibration control of a NREL 5MW wind turbine

The increasing demand for renewable energy has driven the development of larger and more powerful wind turbines designed to optimize energy production under a wide range of operating conditions. However, these larger structures are also subject to significant mechanical stress and fatigue due to highly variable wind loads. These stresses can lead to increased maintenance costs, reduced operational life, and in extreme cases, structural failures.

This chapter introduces the concept of the HSFD and its application to the NREL 5 MW wind turbine model.

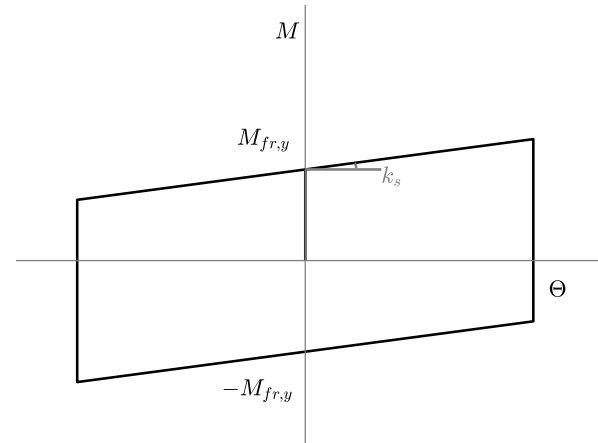


Fig. 3 HSFD ideal cyclic behavior

### 2.1 HSFD

The HSFD (Sorge *et al.* 2024, Fig. 2) is a device designed to improve the structural response of onshore wind turbines by reducing peak stresses and fatigue damage caused by wind loads. Installed at the base of the tower, the HSFD represents a passive control system made of a spherical hinge, coupled with a series of springs and friction devices arranged in parallel to manage the tower's rotations and dissipate the energy coming from the aerodynamic loads. More in detail, the springs provide rotational stiffness at the base of the tower, with the consequent re-centering effect during the wind-induced oscillations. The friction dampers, on the other hand, are responsible for energy dissipation when the bending moment at the base of the tower exceeds the threshold value related to the friction yielding strength (Fig. 3). The design parameters of the HSFD, therefore, are the spring stiffness ( $k_s$ ) and the friction yielding force ( $M_{fr,y}$ ). The optimal ( $k_s, M_{fr,y}$ ) combination has to be identified with the objective of achieving reduction of the peak bending moment and of the cumulative fatigue damage, while ensuring that the base rotation does not exceed a threshold value generally adopted to balance structural safety and operational functionality (0.003 rad, the most common in industrial practice).

### 2.2 Dynamic model of the NREL 5 MW wind turbine

The dynamic model used in this work refers to the 5 MW wind turbine prototype developed by the National Renewable Energy Laboratory (NREL), that is one of the most widely analyzed case-studies in wind energy research. The structural and operational characteristics of the NREL 5 MW turbine have been extensively documented and validated (Jonkman *et al.* 2009), making it an ideal choice for large-scale wind system analysis and simulations.

The turbine tower is 87.60 meters high and consists of a hollow tubular structure with an external diameter variable along the height. At the bottom, the outer diameter is 6.00 meters, while it decreases to 3.87 meters at the top. The wall thickness of the tower is 27 mm at the base while 19 mm at the top. The overall mass of the tower accounts for both structural and non-structural components, such as

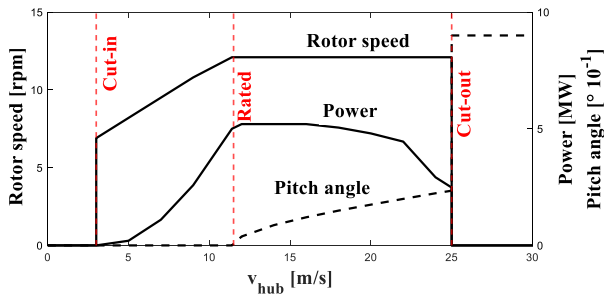


Fig. 4 WTG characteristics in function of the mean velocity (data from Jonkman *et al.* 2009)

cables and electro-mechanical equipment. In terms of structural dynamics, the tower exhibits a natural frequency of 0.28 Hz for the first mode and 2.45 Hz for the second mode.

The NREL 5 MW turbine is a three-bladed system, designed to operate with variable rotor speed. The rotor's overall diameter is 126 meters, and the hub height is 90 meters. This design allows the turbine to optimize energy production over a wide range of wind speeds. Specifically, the turbine operates at three characteristic wind speeds at the hub: cut-in, rated, and cut-out speeds.

- **Cut-in speed:** when the wind reaches 3 m/s in velocity, the turbine begins to operate and generate energy. At this stage, the pitch angle is zero.

- **Rated speed:** the rated wind speed is 11.4 m/s, that is the wind speed that potentially allows the turbine produces the nominal power (5 MW). When the wind speed is higher, the blade pitch angle is adjusted to maintain optimal efficiency, keep the power output stable, and reduce loads on the blades.

- **Cut-out speed:** when the wind speed exceeds 25 m/s, the turbine stops operating to protect the system from potential damage caused by excessive forces. In this scenario, the blade pitch angle is adjusted to a safe position, typically around 90°, to minimize wind exposure and reduce aerodynamic loads to the blades and, consequently, to the tower. The transition towards cut-out state is characterized by a sharp reduction in power output, due to the activation of the braking system, which dissipates energy to safely slow down the rotor.

In Fig. 4, the operational behavior of the NREL 5 MW turbine is illustrated. The rotor speed is shown on the vertical axis on the right, while the turbine's power output in MW and the blade pitch angle in degrees are represented on the left vertical axis. The x-axis shows the mean wind speed at the hub ( $v_{hub}$ ). The three characteristic speeds cut-in, rated, and cut-out are clearly highlighted, along with the corresponding pitch angle adjustments in response to different wind speeds.

The turbine blades have been discretized into eight sections, each designed with a different airfoil profile to maximize aerodynamic performance. The maximum chord length of the blades reaches 4.65 meters. The blade pitch angle varies from 0° to 90° depending on the turbine's operating conditions and wind speed, as said above. In “parking” scenarios, i.e., when the turbine is not in

operation, the blade pitch angle is fully extended to 90°. During normal operation, the pitch angle varies between 0° and 23.45° to optimize energy production and reduce structural loads. This activity was performed using the Qblade software (Marten 2020) to generate the time histories of forces and moments to be applied to the tower, which is the primary subject of investigation.

The tower was modeled using the MATLAB software, discretized into 15 elements to achieve an accurate yet computationally efficient representation of the tower's dynamic behavior. This discretization enables the simulation of tower deformations and its natural frequencies in response to dynamic forces such as wind loads and mechanical vibrations.

### 2.3 Design of the HSFD for the NREL 5MW wind turbine

The optimization procedure for the HSFD is based on the Exhaustive Search (ES) technique (Lara-Valencia *et al.*, 2020), which systematically explores a wide range of combinations of the mechanical parameters  $k_s$  and  $M_{fry}$ .

The objective function defined as a linear combination of two performance indices:

- the first is related to the reduction of the maximum base bending moment.
- the second focuses on reducing the structural fatigue demand.

This function is evaluated for each pair of parameters within the optimization domain  $\Theta=[k_s, M_{fry}]$  and considering two groups of 7 wind cases respectively belonging to the rated and to the cut-out scenarios. The optimization was conducted both on individual wind cases and on aggregated groups for each scenario, and finally, on all 14 cases combined. This was done by Sorge *et al.* (2024), to whom the reader can refer for further details. This approach allowed the identification of the optimal configuration that balances structural requirements under multiple wind loads ( $k_s=24356$  MNm/rad and  $M_{fry}=4.86$  MNm).

The primary objective of this work, as said, is to validate the design by evaluating the effectiveness of the control system under a comprehensive range of wind scenarios. These scenarios vary in intensity and frequency content, encompassing all possible operating states of the turbine.

## 3. Validation of the HSFD design against a comprehensive set of scenarios

The validation of the HSFD was carried out through a series of numerical simulations that analysed the dynamic behaviour of the tower under several operational wind scenarios.

### 3.1 Wind loads and wind load scenarios

The wind speed at the hub height, ranging between the cut-in and cut-out values, was discretized into 13 intervals.

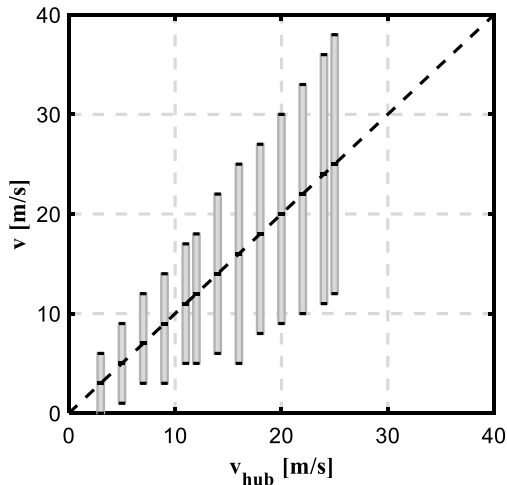


Fig. 5  $v$  ranges derived from the envelope of seven 10-minute wind histories for each  $v_{hub}$  (3–25 m/s)

For each wind speed, 7 randomly generated wind cases were analysed, resulting in a total of 91 cases considered. Fig. 5 shows the range of  $v$  values, spanning from the minimum to the maximum derived from the envelope of seven 10-minute wind histories, considered for each  $v_{hub}$  scenario (3, 5, 7, 9, 11, 12, 14, 16, 18, 20, 22, 24, 25 m/s).

The wind parameters defined according to the IEC64100-1 (2019) standard, and for extreme load analyses, the extreme turbulence model (ETM) was adopted, as recommended by the standard for scenarios in which the turbine is operational.

Fig. 6 shows the thrust force exerted by the rotor on the top of the tower. Two curves are presented: the first, thicker one represents the average peak thrust at the hub calculated from the 7 wind cases for each scenario ( $Thrust_{avg}$ ); the second, thinner one represents the average of the mean thrust for each wind case, also for each scenario ( $Thrust_{max}$ ).

In the scenarios near cut-in, the loads are relatively low but large enough to assess the elastic response of the tower and the contribution of the HSFD in managing minor oscillations. The rated condition (11.4 m/s) represents the full operating capacity of the turbine. In this scenario, aerodynamic forces are higher, and it becomes essential to closely monitor the dynamic behaviour of the tower, ensuring that the HSFD is effective in reducing peak bending moments at the base. Between the rated and cut-out speeds, the peak thrust remains constant, as expected, while the mean thrust decreases. This is explained by the increasing amplitude of oscillations due to the higher rotor speed and the increase in pitch angle. Finally, in the cut-out condition (wind speed exceeding 25 m/s), the turbine shuts down to prevent structural damage. At this stage, it is crucial to verify that the HSFD continues to function effectively, reducing mechanical stresses that could compromise the tower's integrity during extreme events, such as sudden gusts or significant turbulence.

The aerodynamic model of the turbine and wind loads were generated still through a numerical model developed in Qblade (Marten 2020), which includes the temporal and spatial variability of the wind as well as fluctuations due to

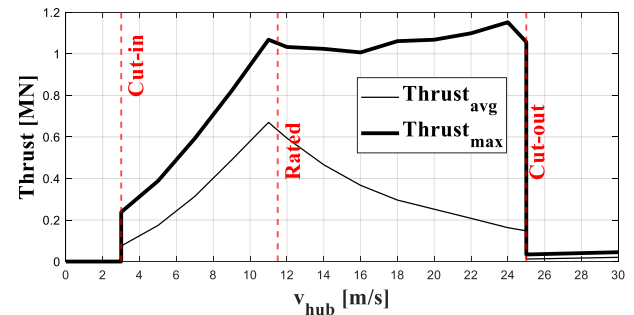


Fig. 6 Average and peak value of rotor thrust at the hub

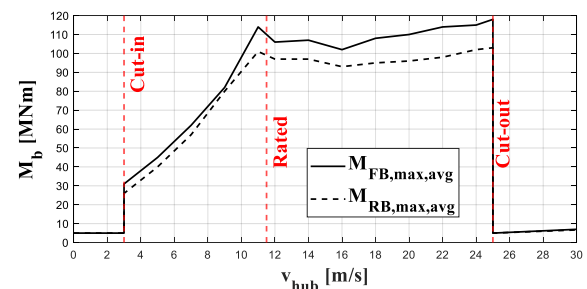


Fig. 7 Average peak bending moment in each scenario: comparison between FB and RB cases

turbulence.

### 3.2 HSFD performance and sensitivity to the input scenario

For each of the 91 above wind loads, the stress state of the tower was analyzed, focusing specifically on the bending moment history at the base. The main objective of this analysis was to assess the actual reduction in bending moment achieved by the calibrated HSFD, comparing the results with the configuration without the device, Fixed Base (FB). For each bending moment history, the peak value was identified and analyzed, which is crucial for determining the effectiveness of the HSFD. In fact, the authors' experience suggests that this is the potentially most critical performance, i.e., the one that (much more than the cyclic fatigue) is most affected by the particular stiffness-friction configuration of the special constraint at the base. However, in a future study, the robustness of the device's performance in terms of fatigue reduction will also be evaluated.

In Fig. 7, two significant curves are presented: the first shows the trend of the average peaks of the bending moment at the base of the FB tower ( $M_{FB,max,avg}$ ), while the second curve ( $M_{RB,max,avg}$ ) represents the same parameter for the tower equipped with the HSFD system (RB). The vertical axis indicates the bending moment ( $M_b$ ), expressed in MN, while the horizontal axis shows the wind speed at the hub, corresponding to the different wind scenarios simulated. For each of the seven wind load cases within each of the 13 simulated sets, the maximum value of the bending moment was evaluated. Subsequently, the average of these seven maximum values was computed for each set.

These averaged values are denoted as  $M_{FB,max,avg}$  and  $M_{RB,max,avg}$  for the FB and RB configurations, respectively. The results obtained from the simulations highlight a consistent reduction in the bending moment peaks in each wind scenario considered, without any scenario showing a worsening of the bending moment compared to the FB configuration.

In the range of wind conditions between cut-in and rated, characterized by low speeds and reduced thrust, the maximum bending moment remains relatively low. However, the HSFD can further reduce this moment by approximately 10-15% compared to the FB configuration, thus ensuring stable behavior even in weak-to-medium wind conditions.

In rated conditions, where stresses are significantly higher, the effectiveness of the HSFD becomes even more evident. In this scenario, the system allows for a reduction in the bending moment at the base of the tower by about 20% compared to the configuration without the device.

In the scenarios between rated and cut-out conditions, the reduction in bending moment remains stable, with a decrease close to 20%, like what is observed at the optimal regime.

Finally, in the cut-out scenario, characterized by extremely high wind speeds, the HSFD continues to ensure a significant reduction at the bending moment, maintaining a reduction of about 20%. This helps to prevent potential structural damage caused by sudden gusts or turbulence.

Another parameter considered in the analysis is the standard deviation of the bending moment peaks. In the FB configuration, it ranges between 2 and 12 MNm, while in the configuration RB it is reduced to a range between 1 and 8 MNm. Overall, an average reduction of about 25% in the standard deviation is observed. This indicates stable and reliable performance of the HSFD under different loading conditions.

In scenarios where stresses are negligible, when the turbine is parked, the influence of the HSFD is reduced, but this is justified by the fact that the forces involved in these cases are of a much lower magnitude. So, this has no relevance for structural safety; rather, it demonstrates that the behavior of the device is as desired (i.e., fixed rotation against moderate loads).

#### 4. Discussion of the results

Analysis of the achieved numerical results clearly demonstrated the effectiveness of the HSFD in reducing structural stresses in the wind turbine tower in all wind scenarios. This result is achieved thanks to the HSFD's ability to combine two main mechanisms: the rotation of the base, which is counteracted by the elastic resistance of the springs, and energy dissipation due to friction. This combination allows for efficient damping of the tower's oscillation amplitude induced by the wind, thus reducing the peak stresses that can compromise the structural integrity and lifespan of the turbine.

The simulations showed that the average reduction of the bending moment at the base of the tower ranges

between 15% and 20%, depending on the operational conditions of the wind turbine and on the specific wind condition. This reduction range is particularly significant in the operational regimes from the rated scenario to the cut-out scenario, where aerodynamic forces reach their highest values. In these conditions, the HSFD's contribution is crucial in limiting stresses and preventing structural damage to the tower and its foundations. Obviously, when designing new turbines, this advantage can be exploited by reducing the tower's cross section and realizing smaller foundations.

When analyzing thrust loads, it is observed that this increases linearly from the cut-in scenario to the rated scenario, and then remains relatively constant between the rated and cut-out regimes (Fig. 6). During this operational range, the loads reach their peak maximum values, which remain stable despite an increase in the amplitude of the force oscillations acting on the structure. It is precisely in this critical phase that the HSFD shows its greatest effectiveness: by reducing the oscillations and, consequently, the peak stresses, the device helps to protect the tower and the foundation.

In extreme regimes, such as the cut-out scenario, where wind speeds reach 25 m/s at the hub, the HSFD demonstrated the ability to reduce the maximum bending moment by up to 20%. This is a highly significant result, as extreme wind events are one of the main causes of damage to wind turbines. Reducing the stresses under these conditions not only helps to prevent critical structural damage during the normal operation of the wind turbine, but also reduces the frequency of maintenance and repair operations, thereby improving the turbine's operational efficiency.

The installation of the HSFD offers important benefits from both a design and economic perspective. The reduction of maximum stresses allows for optimization in the use of materials for the construction of the tower and foundations, permitting a reduction in the over-sizing usually adopted to cope with peak stresses. This translates into a decrease in the production costs of the tower and its foundations, without compromising the turbine's safety and efficiency.

#### 5. Conclusions

The effective performance of a special passive control device (HSFD, Hinge-Spring-Friction Device) for mitigating dynamic stresses acting on wind turbine towers has been analyzed against several wind loads belonging to very different scenarios. This has been done to validate a design procedure drawn in a previous work by the authors, i.e. to assess how the performance of the control system may be affected by the input load in significantly varied cases. Through an extensive series of numerical simulations, the results showed that the HSFD significantly enhances the structural performance of turbines by reducing both bending moments and peak stresses induced by wind loads, especially under operational conditions. This result represents a significant advancement in the research and development of vibration control technologies for wind

turbines, which are constantly exposed to dynamic forces throughout their lifespan.

Optimizing the HSFD parameters proved to be crucial in achieving significant reductions in the maximum moment at the base of the tower and accumulated fatigue, key factors for the durability of turbines. Specifically, it was shown that the HSFD led to a reduction of the bending moment by up to 20% in the most critical operational conditions, namely between the rated and cut-out scenarios. For scenarios with wind speeds below the rated level, the mitigation action is less important, since the bending demand is lower. However, even in that "zone", the control system led to a reduction (10-15%) of the peak moment. It is worth noting that in none of the examined scenarios or wind conditions did the adoption of the HSFD control system worsen the tower's structural response compared to the conventional FB configuration. This is far from an obvious result and is one of the most important findings of this research, as it shows that the device always operates in the direction of higher safety.

The implementation of the HSFD can have positive implications on several fronts. Environmentally, greater reliability and durability of wind turbines result in a reduced need for component replacement, and thus a lower production of waste and environmental impact. From an economic standpoint, extending the operational life of turbines and reducing structural stress can contribute to a significant decrease in operating costs, enhancing the return on investment for operators in the wind industry.

Looking ahead, there are several research directions that could be explored to further improve the effectiveness of the HSFD. Firstly, the development of even more advanced optimization models, capable of considering a greater number of parameters and load scenarios, could increase the efficiency of the device. Another relevant aspect concerns the study of HSFD behavior under extreme loads, such as those caused by typhoons or severe weather events, which represent a growing challenge for wind turbines in various parts of the world.

Furthermore, it will be essential to validate the numerical simulation results with scaled experiments, using operational wind turbines in controlled environments.

It should be emphasised that the present work represents an intermediate step in the research aimed at a comprehensive numerical validation of the effectiveness of the HSFD device. The results obtained have demonstrated the ability of the system to significantly reduce structural requirements over a wide range of realistic loading scenarios. The next planned development involves scaled physical implementation and experimental testing of the device, with the aim of confirming the simulated performance and facilitating its technology transfer to the wind energy industry.

Being aware of the simplifications adopted at the modelling stage, a natural extension of this work will involve the integration of more accurate structural models, combined with the use of advanced aerodynamic modelling capable of more realistically capturing turbulent and unsteady flow conditions. This will allow a more comprehensive assessment of the dynamic interactions

between the blades and the tower, further improving the understanding of the system behaviour under complex operating conditions.

## Acknowledgements

The authors acknowledge the support of the ReLUIIS 2024-26 project for having financed this research, in the framework of the work package No. 15 'Isolation and dissipation devices and systems'. The authors also acknowledge the Department of Engineering of the University of Naples 'Parthenope' for funding the open-access publication of this work.

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