Vibration-based monitoring of a small-scale wind turbine blade under varying climate and operational conditions. Part II: A numerical benchmark

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Summary
This paper constitutes the numerical companion of the experimental work on vibration-based monitoring of a small-scale wind turbine (WT) blade. In this second part, a numerical benchmark is established for condition assessment of a Windspot 3.5-kW WT blade. The aim is to supplement the companion experimental work with a physical model exposed to diverse operational conditions, loading scenarios, and damage patterns that are not easily explorable and controllable in the laboratory. To this end, a finite element (FE) model of the considered blade is developed and subjected to a number of artificial damage scenarios, which are dynamically tested under both environmental and operational variability. The paper offers a detailed description of the numerical benchmark and the underlying assumptions, as well as the spectrum of operational conditions, the measured quantities, and the wind load model. Finally, we provide an overview and demonstration of the stand-alone application for time history analysis and generation of synthetic vibration data, which is made available via an open-access code in Sonkyo-Benchmark repository.

KEYWORDS
condition assessment, damage detection, numerical benchmark, operational and environmental variability, structural health monitoring, system identification, wind turbine blade

1 | INTRODUCTION

With wind energy following a rapid development during the few decades, its host infrastructure has in turn experienced an equally noticeable advancement. This progress may be easily evidenced by the increased size of modern machines, which is on the one hand associated with higher power capacity but on the other hand accompanied by a number of challenges. For safeguarding the wind turbine (WT) infrastructure and optimizing output from such systems, Structural health monitoring (SHM) emerges as a critical process, aiming to devise an appropriate operation and maintenance (O&M) strategy for the major structural components, namely, blades and support structure. This may be materialized...
through the synergy of an efficient control scheme and an accurate, as well as reliable, vibration monitoring system, able to provide an assessment of the system's structural performance and reliability.

One of the major technical challenges related to vibration monitoring of blades stems from the intricate dynamics and the intrinsic uncertainties, which render simulation-based approaches nontrivial to implement. Therefore, the numerical investigation of vibration characteristics should be based on a reliable and efficient aeroelastic model, which should enable the coupling of a structural and an aerodynamic part. The former is usually modeled with equivalent beam elements, while typical aeroelastic modeling approaches for WTs include the Blade Element Momentum (BEM) theory, the actuator line model, the lifting panel and vortex model, and computational fluid dynamics (CFD) approaches. The actuator line, as well as the lifting panel and vortex model, is intended to provide an improved modeling of wakes; however, both of them are characterized by individual weaknesses, with the former being computationally demanding due to the requirement for solving the Navier–Stokes equations and the latter suffering from divergence issues owed to the intrinsic singularities of the method. CFD analyses are on the other hand receiving significant attention, albeit currently shown to be unreliable for high angles of attack. Moreover, their applicability remains limited by the increased computational demands. As such, BEM theory has established itself as the standard industrial practice for predicting aerodynamic loads on WT blades, which is owed to the ability of providing accurate and computationally efficient results using airfoil aerodynamic data.

Various alternative approaches have been proposed, apart from the well-established aerodynamic models described above. An extensive review study in that respect is provided in Zhang and Huang, with emphasis on instability problems, complex inflow effects, structural nonlinearities, and CFD and aerohydroelastic analyses. To what concerns the aerodynamic part alone, the use of modified strip theory for the performance of aeroelastic analysis has been proposed in Lee et al. while an aeroelastic scheme based on the harmonic balance method has been also presented, achieving significantly reduced computational times and proving more robust than standard BEM approaches. The effect of ice accretion on the aerodynamic behavior of blades is further addressed, by conducting a numerical study using three-dimensional models. A class of more sophisticated methods pertains to CFD-based analyses, which are proven to provide reasonable agreement with standard industrial tools, such as Fatigue, Aerodynamics, Structures, and Turbulence (FAST). With regard to the structural model, methods beyond the standard approach, which consists of the construction of equivalent beams, have also been proposed, including thin-walled beam models that can accommodate the majority of features encountered in large-scale blades, such as arbitrary laminate layups and shear deformability, as well as models accounting for the progressive damage due to dynamic loading, among others. Lastly, Peeters et al. constitute an interesting comparative study on the static behavior between shell and solid finite element (FE) models for blades.

The bulk of standard practice in industrial applications is wrapped in a number of available aeroelastic software, such as Program for Horizontal Axis wind Turbine Analysis and Simulation (PHATAS), GH-Bladed, ASHES, and FAST. In their majority, commercial simulators are based on linear elastic models, which are not able to take into account the effect of large displacements, neither on the response itself nor on the wind loads. Although these effects are negligible for small-scale blades, this is not the case for large and flexible ones, which usually experience significant geometric nonlinearities. Moreover, as the size of today's WTs increases, the blades are in turn more flexible, and coupling effects due to geometric nonlinearities become more and more relevant. Among the various in-house codes and software for aeroelastic modeling, Horizontal Axis Wind turbine simulation Code 2nd generation (HAWC2) provides one of the few nonlinear commercial simulators, which is developed by Technical University of Denmark (DTU) and combines BEM theory with a multibody formulation to model geometric effects.

A further method for addressing the problem of large displacements for WT blades, which is becoming increasingly relevant for larger WTs, is the geometrically exact beam theory (GEBT), which essentially provides an exact representation of the deformed beam geometry. One of the drawbacks though related to the solution of a typical displacement-based formulation of GEBT is the increased computational cost. A remedy to this was provided by the implementation of a mixed-form formulation, which has been widely used for aircraft wing applications. This formulation was relatively recently implemented and validated and subsequently further fused with BEM theory to develop a nonlinear aeroelastic model for WT blades. A class of alternative approaches to alleviate increased computational cost lies in use of reduced-order models, which may be well based on the use of nonlinear normal modes (NNMs). A number of more recent works are focused on the coupled behavior of blade response, with the latter dealing with the geometric effects of three-dimensional blade models, which are taken into account using a substructuring approach, enhanced with modal derivatives. The method is demonstrated to achieve remarkable computational efficiency, enabling thus the coupling with structural monitoring data for real-time applications. Lastly, the
usefulness of establishing a multifidelity framework was highlighted in Abdallah et al.\(^4\) enabling thus the efficient treatment of outputs from diverse simulators.

In facilitating exploitation of physical modeling and associated considerations, the second part of these companion papers describes a numerical benchmark, focused on the investigation of vibration-based monitoring for the small-scale Windspot 3.5-kW WT blade by Sonkyo.\(^3\) Within this context, a three-dimensional FE model of the blade is constructed in order to supplement the experimental work conducted in Part I with operational conditions, loading scenarios, damage patterns, and modeling aspects that are not straightforwardly implementable in the experimental setup. The model is subjected to a series of flaws, which are selected in accordance with those introduced in Part I, and further allows for an aeroelastic analysis across the entire operational and environmental spectrum of the Windspot 3.5-kW WT. To do so, an open-access model library, which encompasses the physics and damage features described herein, is further developed and made available in conjunction with this paper. A default setup of the benchmark and associated code is elaborated upon herein. Interested researchers are encouraged to further contribute by proposing additional scenarios, functionalities, and enhancements to be integrated to the open-access tool.

The main driver for the development of this companion work stems from the need to address certain challenges and aspects, which characterize the vibration of WT blades and are not reproducible in the experimental part. Concretely, the most critical influence on the vibrational properties of the blade, apart from environmental variability, is exerted by the varying operational conditions (rotation). These are now taken into account in this numerical benchmark counterpart. Moreover, the experimentally resource-limited damage scenarios can be further extended and investigated, under well-posed and fully quantifiable system conditions, while vibration response data can be now generated by means of a realistic aerodynamic loading, instead of a point load excitation. Lastly, the sensing information can be herein extracted from an extensive multitype measurement grid, sidestepping thus the restrictions owed to the physically confined surface of the specimen and the limited availability of sensing resources. The aforementioned complementary features enable the utilization of the here delivered simulator as a vehicle for rigorously validating and corroborating the wide range of condition assessment, SHM, and system identification methods. As such, it should be underlined that the present work is not intended to serve as a simulator, which targets the modeling of complex actual-scale blades. Instead, the aim is to provide a standardized simulator for the SHM community, which can establish itself as a reference point in the realm of inverse engineering and which draws inspiration from SHM for wind energy infrastructure.

The paper is structured as follows: Section 2 provides a thorough description of the numerical model and the underlying assumptions. The dynamic properties of the model across the entire spectrum of environmental and operational conditions are subsequently documented in Section 3, while Section 4 presents the simulated damage patterns, in accordance with those adopted in the experimental part. Section 5 deals with the proposed procedure for aeroelastic analysis, which is mostly focused on the adopted approach to generate aerodynamic loads for three-dimensional FE models. Lastly, Section 6 constitutes a brief documentation of the publicly available application for data generation, which is accessible via the Sonkyo-Benchmark GitHub repository.

## 2 | MODEL DESCRIPTION

The Sonkyo Windspot 3.5-kW blade is 1.75 m long with a total mass of 5.0 kg and consists of three major structural components. These are the outer shell of 0.93-mm thickness, the inner fill, and four stiffeners of 1.2-mm thickness contributing in flap-wise direction and spanning from the transition zone close to the root up to the mid of the length. To numerically represent the specimen, a three-dimensional high-fidelity FE model is constructed, which comprises two different types of elements: a first-order (linear) six-degree-of-freedom thin shell for the outer surface and the stiffeners and a first-order solid for the foam. Both types of elements are employed with a reduced-integration scheme and hourglass control, while the latter is further minimized by using a sufficiently fine mesh. The reader is referred to the Abaqus theory manual\(^4\) for further details related to the formulation of the elements.

To ensure that all three constituents form a single entity, the foam is tied to the outer shell and the stiffeners by using matching meshes at the interfaces, while the stiffeners are tied, due to nonconforming interfaces, to the shell using multipoint constraints. Lastly, the boundary conditions are applied in accordance with those on Windspot 3.5-kW WT, creating a fixed-free setup as shown in Figure 1. In order for the discretized model to remain as close as possible to the actual curved geometry and further be able to accommodate the introduction of localized flaws, in the form of damage, the average element size is equal to 1.5 mm, resulting thus to a total of 1.066.178 quadrilateral
elements and around 6M degrees of freedom. The mesh of the sliced model, with close-up view at the leading and trailing edges, is depicted in Figure 2.

It should be noted that the present study aims at establishing a benchmark model, which is able to reflect the effect of local system changes. This inevitably calls for a three-dimensional model, in place of a beam equivalent. The latter may be computationally efficient, even when nonlinear effects are included, but not capable of accommodating localized flaws, such as damage or cracks. Within this context, the options for performing aeroelastic analysis using a three-dimensional FE model are mainly limited to CFD approaches, which may become prohibitively expensive for the vibration response simulation of the blade across various samples of the operational and environmental space. As such, the computational efficiency of the benchmark presented in this paper is initially ensured by performing an order-reduction step at the level of the model and subsequently by adopting a hybrid scheme for the aeroelastic loading, which is meticulously described in Section 5.

The FE model is simulated using an in-house MATLAB library which is partially made available in the project repository. Concretely, a full-order version of the model is initially developed, encapsulating the features described below, and subsequently transformed to a reduced space of generalized coordinates, in order to enable efficient computational times for aeroelastic analysis. It should be noted that a single simulation of the full model would not be significantly expensive in terms of computational time. However, the cumulative cost for the simulation of various samples across the environmental and operational space, as well as for different damage states, may quickly become prohibitively expensive and hence the reduction step. The reduced space is parameterized with respect to the ambient temperature and the rotational speed, so as to allow for the simulation of the vibration response across the entire environmental and operational spectrum. In this regard, the reconfiguration of geometry, material properties, and boundary conditions is not directly applicable in the MATLAB code; however, the database can be retrained and updated, in order to accommodate additional configurations and damage scenarios, upon request in the project repository. A detailed description of the default library functionalities is provided in Section 6, which also serves as a short documentation of the provided MATLAB application.
Although the size of the Sonkyo blade is significantly smaller than that of the blades used in modern WTs, which may well reach a length of 100 m, this paper addresses some of the major non-size-specific challenges encountered in the SHM of such structures. These are associated with the system changes induced by operational and environmental variability. These naturally scale differently in small- and large-scale systems, but their physics, excluding large displacement effects, which are more relevant to large-scale blades, are qualitatively identical and equally important for both small- and large-scale turbines.

2.1 Material properties

The outer shell and the stiffeners are manufactured from a double layered composite material with orthotropic properties, referred to as combi mat, while the inner fill is made of an isotropic and linear elastic polyurethane foam. Although the material properties of foam are properly defined, the behavior of combi mat depends on the properties and orientation of individual layers, which are not known a priori. In this sense, the characterization of combi mat is herein carried out by an inverse process, whereby the six engineering constants \( E_1, E_2, E_3, G_{12}, G_{13}, \) and \( G_{23} \) of the effective material, comprising all individual layers, are calibrated in order to achieve a good agreement between the dynamic properties of the model at 25°C and those identified from the experimental specimen at the same temperature.

The values of the moduli obtained from such a process are reported in Table 1. Thereafter, the dependency of material properties, namely, the six engineering constants, on temperature is imposed by means of existing temperature models borrowed from the literature for fiberglass composites. The underlying temperature dependency model is applied on every single modulus \( M_i \), yielding the dependency law depicted in Figure 3, which is analytically represented by the following formula:

\[
M_i = a_i e^{b_i T} + c_i, \quad \text{for } i = 1, 2, ..., 6
\]

where \( T \) [°C] denotes the temperature and \( a_i, b_i, \) and \( c_i \) are modulus-specific parameters whose values are documented in Table 1.

| Engineering | Description                 | Value  | Unit | Parameters constants |
|-------------|-----------------------------|--------|------|----------------------|
|             |                             |        |      | \( a_i \) | \( b_i \) | \( c_i \) |
| \( E_1 \)   | Axial modulus               | 11.984 | GPa  | −0.411 | 0.071 | 14.409 |
| \( E_2 \)   | Transverse modulus          | 12.823 | GPa  | −0.588 | 0.064 | 15.736 |
| \( E_3 \)   | Out-of-plane modulus        | 8.108  | GPa  | −1.257 | 0.054 | 12.957 |
| \( \nu_{12} \) | Poisson ratio               | 0.25   | -    | -      | -     | -      |
| \( \nu_{13} \) | Poisson ratio               | 0.25   | -    | -      | -     | -      |
| \( \nu_{23} \) | Poisson ratio               | 0.25   | -    | -      | -     | -      |
| \( G_{12} \) | In-plane shear modulus      | 4.157  | GPa  | −0.253 | 0.058 | 5.236  |
| \( G_{13} \) | Out-of-plane shear modulus  | 5.802  | GPa  | −0.383 | 0.057 | 7.395  |
| \( G_{23} \) | Out-of-plane shear modulus  | 0.648  | GPa  | −0.019 | 0.073 | 0.766  |

![Figure 3](image-url) Variation of the principal moduli of elasticity (left) and shear moduli (right) with temperature.
3 | DYNAMIC PROPERTIES

To provide an overview of the constructed FE model, this section is focused on the presentation of the dynamic properties and their correspondence to those obtained from experiments. As underlined in the previous section, the effective material properties are identified at 25°C temperature. The first eight vibration modes, along with their natural frequencies, are illustrated in Figure 4. It is shown that apart from edgewise modes, which are not identified in the experimental part due to the adopted sensor setup, the frequencies of both flap-wise and torsional modes exhibit a sufficiently good agreement with the experiments.

This section further aims at illustrating and quantifying the change in modal properties induced by the different sources of variability acting on the blade. A primary factor influencing the dynamic features of a WT system in general, and a blade in particular, lies in environmental fluctuations, namely, humidity and temperature variability. As demonstrated in the experimental companion paper, the effect of humidity is barely noticeable on the blade properties, while temperature exerts a well pronounced impact, especially in the low temperature range. The influence of ambient temperature on the vibration modes of the numerical model follows from the aforementioned assumption of temperature dependence for the engineering constants. This is illustrated via the resulting change in natural frequencies, as shown in Figure 5.

Apart from environmental effects, WTs are additionally exposed to operational variability, that is, the variability linked to loading variations. A main operational factor, affecting the dynamic features, is owed to the centrifugal forces.
These result in a stiffening effect on the blades, thereby increasing the natural frequencies with respect to the stationary, that is, idling, conditions. Such an effect plays a considerable role in the design process and is meticulously analyzed for avoiding resonance with the numerous operating harmonics. Moreover, it is equally relevant in the context of SHM, since it can mask actual system changes and therefore render condition assessment unfruitful. As such, the centrifugal effect is herein taken into account by means of a nonlinear analysis, which allows for modeling of the stiffening behavior. The impact on the natural frequencies of the model developed herein is illustrated via the Campbell diagram, which is shown in Figure 6 for the entire operating regime of the WT.

4 | DAMAGE SCENARIOS

As in the experimental study, which is thoroughly described in the companion paper, the blade is herein considered in an initially healthy condition, the so-called reference state, and subsequently modeled under a number of damage
scenarios across the entire environmental and operational spectrum. It should be noted that this work is not intended to be a numerical duplicate of the companion experimental paper, and therefore, it does not aim at providing identical findings. Instead, it constitutes supplementary work that can take into account effects and physics that are not easily explorabile and controllable in the laboratory and under resource-constrained conditions. The default types of flaws are identical to those introduced in the experimental specimen, which are, similarly to the companion paper, determined on the basis of existing experimental\textsuperscript{45} and numerical\textsuperscript{46} contributions in which the damage-critical locations on WT blades are reported.\textsuperscript{47,48} However, each scenario is now modified to more realistically capture the physics in-operation, as well as for simulating the intended flaws as precisely as possible.

Concretely, the first three scenarios, which are intended to simulate icing accretion, but may well further represent other types of damage, comprise the insertion of additional mass on the surface of the blade. In order to achieve an as realistic as possible representation, the mass is not placed locally on a single point but is distributed on the nodes of the affected area as shown in Figure 7. The remaining damage scenarios, which consist of cracks of different characteristics, are materialized by introducing stiffness reduction on a 2-mm width band of elements. For these scenarios, the laboratory-controlled features, such as position and length, are identical to the ones used for testing. However, the percentage of damage is now precisely regulated to 20\%, 50\%, and 80\% for each one of the cracks. This results in the same number of damaged cases, with the difference that each one comprises all possible combinations of damage severity between cracks, leading thus to a total of 205 simulation cases, which are reported in Table 2.

It should be clarified that the employed damage scenarios constitute only a subset of the possible flaws encountered in WT blades,\textsuperscript{45} which are in vast majority of literature reproduced in laboratory conditions. As such, it cannot be directly deduced that such scenarios would be typically expected in operational conditions; however, the considered damage locations are the ones where the highest stress concentrations are observed under operational loads and likely the most sensitive ones.

5 | RESPONSE SIMULATION

In contrast with the companion paper, where the experimental specimen is excited with a point load applied via a shaker device, the dynamic response of the blade is herein obtained by means of an aeroelastic analysis. By so doing, the equations of motion of the blade, which are obtained from the FE model as follows:

\[
M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F_a(u(t),t) + F_g(t)
\]  

(2)

are solved for fully operational conditions. In the above equations, \(F_a(u(t),t)\) denotes the vector of aerodynamic forces, the calculation of which will be extensively elaborated below, and \(F_g(t)\) is the gravity force vector which is applied on each and every node \(i\) of the model according to the following expression:

\[
F_g^i(t) = \begin{bmatrix}
\cos \beta & \sin \beta & 0 \\
-\sin \beta & \cos \beta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
-g \cdot m_i \\
0 \\
0
\end{bmatrix}
\]  

(3)
where $\beta$ is the azimuth angle, describing the position of the blade in the circumferential direction of the WT axis, $g$ denotes the gravitational acceleration, and $m_i$ is the $i$th nodal mass. It should be noted that the tilt angle, between the shaft and the horizontal axis, is herein assumed to be zero.

The state of the art in aeroelastic modeling for WTs\textsuperscript{49} ranges from the simple BEM theory up to CFD analyses, while the reader is also referred to a more recent review.\textsuperscript{50} The standard industrial practice for predicting aerodynamic loads on WT blades lies in use the of BEM theory.\textsuperscript{51,52} However, the one-dimensional loads (drag, lift, and aerodynamic moment) obtained from such an approach are not directly applicable to three-dimensional FE models.\textsuperscript{53} Although Griffith and Ashwill\textsuperscript{54} combined 3-D FE models with BEM based loads, it was shown\textsuperscript{53,55} that such an approach may lead to artifacts in the structural response, such as fictitious stress peaks.

A number of alternatives has been investigated in that respect,\textsuperscript{56} proposing a mapping technique to apply realistic wind loads to shell FE models in order to avoid computationally expensive remedies, such as fluid dynamics or fluid–structure interaction problems. Despite the satisfactory agreement with response obtained from one-dimensional loads, the results were lacking a solid comparison with high-fidelity reference solutions. To this end, a comparison of the three most commonly used loading approximations for three-dimensional FE models is provided in Barnes et al.\textsuperscript{57} including 3-D pressure distributions obtained from a CFD analysis, uniform pressure derived from BEM, and a single tip load obtained from BEM and beam theory. With the exception of point load, it was shown that mapping of BEM loads to three-dimensional blades may yield an accurate representation of the blade stress condition, while maintaining the computational efficiency.

In view of these aspects and in order to provide a realistic representation of aerodynamic loads, this study is based on the pressure distribution at the level of airfoils, which can be derived from dedicated software for design and analysis of airfoils, such as XFOIL\textsuperscript{58} and RFOIL,\textsuperscript{59} the modified and improved version of the former. Such an approach was initially proposed, albeit not implemented, in Bottasso et al.\textsuperscript{60} towards the enhancement of wind loads in the context of structural optimization and in Fernandez et al.\textsuperscript{61} was recently integrated into a hybrid scheme, combining Xfoil

| Case label | Description |
|------------|-------------|
| R | Healthy state |
| A | Added mass $1 \times 44$ gr, distributed over 44 nodes |
| B | Added mass $2 \times 44$ gr, distributed over 88 nodes |
| C | Added mass $3 \times 44$ gr, distributed over 132 nodes |
| D | Crack 1: $l_1 = 5$ cm $d_1 = 20\%, 50\%, 80\%$ |
| E | Crack 1: $l_1 = 5$ cm $d_1 = 20\%, 50\%, 80\%$ Crack 2: $l_2 = 5$ cm $d_2 = 20\%, 50\%, 80\%$ |
| F | Crack 1: $l_1 = 5$ cm $d_1 = 20\%, 50\%, 80\%$ Crack 2: $l_2 = 5$ cm $d_2 = 20\%, 50\%, 80\%$ Crack 3: $l_3 = 5$ cm $d_3 = 20\%, 50\%, 80\%$ |
| G | Crack 1: $l_1 = 10$ cm $d_1 = 20\%, 50\%, 80\%$ Crack 2: $l_2 = 5$ cm $d_2 = 20\%, 50\%, 80\%$ Crack 3: $l_3 = 5$ cm $d_3 = 20\%, 50\%, 80\%$ |
| H | Crack 1: $l_1 = 10$ cm $d_1 = 20\%, 50\%, 80\%$ Crack 2: $l_2 = 10$ cm $d_2 = 20\%, 50\%, 80\%$ Crack 3: $l_3 = 5$ cm $d_3 = 20\%, 50\%, 80\%$ |
| I | Crack 1: $l_1 = 10$ cm $d_1 = 20\%, 50\%, 80\%$ Crack 2: $l_2 = 10$ cm $d_2 = 20\%, 50\%, 80\%$ Crack 3: $l_3 = 10$ cm $d_3 = 20\%, 50\%, 80\%$ |
| J | Crack 1: $l_1 = 15$ cm $d_1 = 20\%, 50\%, 80\%$ Crack 2: $l_2 = 10$ cm $d_2 = 20\%, 50\%, 80\%$ Crack 3: $l_3 = 10$ cm $d_3 = 20\%, 50\%, 80\%$ |
| K | Crack 1: $l_1 = 15$ cm $d_1 = 20\%, 50\%, 80\%$ Crack 2: $l_2 = 15$ cm $d_2 = 20\%, 50\%, 80\%$ Crack 3: $l_3 = 10$ cm $d_3 = 20\%, 50\%, 80\%$ |
| L | Crack 1: $l_1 = 15$ cm $d_1 = 20\%, 50\%, 80\%$ Crack 2: $l_2 = 15$ cm $d_2 = 20\%, 50\%, 80\%$ Crack 3: $l_3 = 15$ cm $d_3 = 20\%, 50\%, 80\%$ |
pressure distributions with BEM information. In a similar manner, wind loads are herein obtained by discretizing the blade into a number of blade elements and subsequently calculating the angle of attack on each blade element using BEM theory. To do so, the lift and drag coefficients of the airfoils for different angles of attack are calculated with the aid of Xfoil, as shown in Figure 8. To account for the different relative wind speeds seen by positions along the blade, these coefficients are precomputed for a range of Reynolds numbers. Although the upper limit of the latter is determined by the rated operating conditions of the WT, the lower limit is dictated by the flow separation regime which is placed at 100 000 according to van Treuren.62 Having determined the angle of attack, the pressure distribution over the central section of each blade element can be obtained again using Xfoil, as illustrated in Figures 9 and 10, while the pressure at intermediate points can be computed by interpolation.

The detailed steps for wind load computation on each blade element and within each time step are summarized in the following points:
1. Initialization of the axial $\alpha_0$ and angular $\alpha'_0$ induction factors.
2. Initiation of the iterative procedure, by calculating the inflow angle and tip loss factor
   \[
   \phi_k = \arctan\left(\frac{(1 - \alpha_k) V_o + u_{op}}{(1 + \alpha'_k) \Omega r + u_{ip}}\right)
   \]
   \[
   f_{tip,k} = \left(\frac{2}{\sigma}\right) \cos^{-1}\left[\exp\left(-\frac{(B/2)(1-r/R)}{(r/R)\sin \phi_k}\right)\right]
   \]

where $v_{op}$ and $v_{ip}$ are the in-plane and out-of-plane blade element velocities, $V_o$ is the wind velocity, $\Omega$ is the rotor speed, $r$ is the distance of blade element to the rotor center, $B$ is the number of blades, and $R$ the blade radius, as depicted in Figure 9.

3. Calculation of the local angle of attack and determination of the lift $C_l$ and drag $C_d$ coefficients from the airfoil lift and drag versus angle of attack curves (Figure 8)
   \[
   a_k = \phi_k - \theta
   \]

where $\theta$ is the local pitch, which is a combination of the pitch twist angles of the blade.

4. Update of the axial and angular induction factors
   \[
   \alpha_k = \frac{1}{4f_{tip,k} \sin^2 \phi_k} \frac{1}{1 + \frac{\alpha_H(C_{l,k} \cos \phi_k + C_{d,k} \sin \phi_k)}{\alpha_H(C_{l,k} \sin \phi_k - C_{d,k} \cos \phi_k)}}
   \]
   \[
   \alpha'_k = \frac{1}{4f_{tip,k} \sin \phi_k \cos \phi_k} \frac{1}{\sigma(C_{l,k} \sin \phi_k - C_{d,k} \cos \phi_k)} - 1
   \]

where $\sigma$ is the local solidity and $H$ is a correction factor, activated when the axial induction is large.\(^{20}\)

5. Repetition of Steps 2–4 until convergence of the induction factors is achieved within an acceptable tolerance.

6. Upon convergence, the angle of attack and Reynold’s number are used to calculate the distribution of pressure coefficient $C_p(x,y)$ over the airfoil of blade element, as depicted in Figure 10, and the surface pressure exerted at location $(x,y)$ is obtained as follows:
   \[
   C_p(x,y) = \frac{p(x,y) - p_\infty}{\frac{1}{2} \rho V_\infty^2}
   \]

where $p_\infty$ is the free stream pressure, $\rho$ is the air density, and $V_\infty$ is the free-stream wind speed.

7. Interpolation of pressure at intermediate locations.
To simulate the vibration response of the blade, the entire process of load calculation is incorporated into a Newmark integration scheme, which is utilized for the solution of Equation (3) assuming zero initial conditions. The nonlinear terms in the equation of motion, which arise due to the coupling of aerodynamics with the structural vibrations, are handled by integrating a Newton–Raphson iterator within each time-step solution of the dynamics equation. Given the uncertainty and variability associated with the damping mechanisms acting on an operating WT blade, the amount of viscous damping experienced by the structure is herein not completely predefined. Namely, the aeroelastic damping is already introduced due to the coupling of the structural response with the wind field, and the possibility of specifying the structural one is given by means of a proportional damping assumption, where the damping matrix is given by $C = \alpha M + \beta K$, and is for the user to determine. Indicatively, it should be mentioned that for glass fibers, a hysteretic damping factor $\alpha = 0.008$ with $C = \alpha M$ is proposed by Burton et al.\textsuperscript{63} while a number of experimental approaches\textsuperscript{49,64} and numerical approximations\textsuperscript{63,65} for aeroelastic damping are also available.

## 6 DATA GENERATION AND RESULTS

The different structural models, along with the previously overviewed operational and environmental conditions, and the above-described procedure for response simulation are incorporated into an open-access MATLAB code, which is made available on the Sonkyo-Benchmark GitHub repository. The code is wrapped with a graphical user interface (GUI) and enables the dynamic simulation of the blade under different environmental and operational conditions, as well as the extraction of acceleration and strain measurements from a number of virtual sensors. These are arranged in a canonical grid, measuring accelerations in all three directions and in-plane strains, that is, $\epsilon_x$, $\epsilon_y$, and $\tau_{xy}$ in the global coordinate system, as illustrated in Figure 7.

A snapshot of the data generation GUI is shown in Figure 11, whereby the user is initially called to select a model case among the 13 different scenarios documented in Table 2. Upon selection, the model features are displayed in the “Model preview” frame along with a short description. For the group of model cases containing cracks, that is, Damage D–L, the percentage of damage severity for each flaw can be chosen, among the options of 20%, 50%, and 80%. To finalize model definition, the user is asked to indicate the name of output file and optionally select a sensor setup. By default, the acceleration and strain signals are exported for all measurement channels; however, the option of five sparser sensor layouts is also provided for space-saving reasons.
Upon selection of the model settings, the operational and environmental conditions, for which the analysis will be performed, should be defined. These include environmental temperature, rotor speed, pitch angle, mean wind speed, and a load seed ranging from 1 to 10. Apart from temperature, all other parameters are only relevant for time history analysis for which the corresponding settings, that is, total simulation time and size of time step, must be also specified. Moreover, the coefficients $\alpha$ and $\beta$ referring to proportional damping can be optionally defined. Thereafter, the analysis can be executed by clicking on “Submit” button, and the progress will be printed in “Message” window. Lastly, once the analysis is completed, the results will be stored in a .mat file using the name specified in model definition. The vibration response data generated by the proposed simulator are noise free; however, the users are urged to pollute their data as much as deemed necessary in order to illustrate the performance limits of their algorithms.

In order to provide an overview of the different scenarios established in this benchmark, this section is focused on the presentation of the identification results from the most representative damage cases. Due to the wide range of simulation cases and the dense grid of measurement points, the results are compared and presented in terms of the identified dynamic properties. To this end, the considered cases are first simulated using the open-access tool, and the response data at characteristic sensing locations are used for identifying a number of dynamic properties and subsequently illustrating the effect of the three different cracks thereto. This is accomplished by exploring the sensitivity of the natural frequencies, the transmissibilities, and the mode shape curvatures, for all six scenarios including cracks, namely, Cases D–L, in idling conditions at 15°C temperature.

### 6.1 Natural frequencies

In order to highlight the impact of each crack on the identified natural frequencies, the models are divided into three groups, based on the location of the introduced damage, and the power spectral density (PSD) plots are presented in Figure 14a–c. Concretely, Figure 14a depicts the effect of Crack 1, whose location is shown in Figure 7, on the second flap-wise natural frequency by comparing the PSD of the tip acceleration between the reference model R and models D, G, and J. It is shown that a damaged region whose length is comparable to the distance of the stiffeners, as is the case with Crack 1 of 5c-m length, has a barely noticeable effect on the second vibration mode. On the other hand, an increased length of Crack 1, as this case with models G and J, results to a more visible frequency shift, which is still comparable to the changes induced by operational and environmental variability. Accordingly, Figure 14b depicts the effect of Crack 2 on the first flap-wise frequency. Likewise the previous case, it is observed that the change in frequency is of the same order of magnitude for all three models E, H, and K, which can be attributed to the fact that Crack 2 is located in the vicinity of the trailing edge, having thus a minor effect on the flap-wise bending behavior. The effect of the third crack on the second flap-wise frequency is presented in Figure 14c, where a similar picture to Figure 14a,b is observed in terms of sensitivity to the introduced damage. It should be noted that the results presented in Figure 14a–c verify that the natural frequencies alone do not constitute a damage sensitive feature which would be able to consistently distinguish structural damage from environmental- or operational-induced changes.

### 6.2 Transmissibilities

Transmissibility functions (TFs) have been widely used in the SHM literature for both damage detection and localization.\(^{66}\) Their applicability to such problems is mainly owed to their high sensitivity to damage and the fact their extraction does not require any excitation measurement. In practice, TFs are mathematical representations of output-to-output relationships, which can be established in both frequency and time domain. Figure 13a–c depicts the TFs TF1, TF2, and TF3, as defined in Figure 12. Concretely, Figure 13 illustrates the change in TF1, which is owed to Crack 1, in the frequency range between 50 and 75 Hz, while Figure 13b,c depicts the changes in TF2 and TF3, which are more pronounced than the corresponding natural frequency changes presented in Figure 14b,c.

### 6.3 Mode shape curvatures

This section is focused on the investigation of mode shape curvature\(^{67}\) in order to demonstrate the identifiability of the different crack scenarios when more localized features are considered. Figure 15a–c presents the absolute difference
Figure 12: Measurement points used for the extraction of dynamic features.

Figure 13: Transmissibility functions TF1, TF2, and TF3 for all damage scenarios involving cracks; results are extracted in idling conditions at 15°C temperature.

Figure 14: Power spectral density of the tip acceleration signal for all damage scenarios involving cracks; figures (a–c) present a close-up of the power spectral densities in the vicinity of the first and second flap-wise natural frequencies.

Figure 15: Absolute difference of mode shape curvature between the reference model and the models with cracks; results are extracted in idling conditions at 15°C temperature.
between the mode shape curvature of the reference model and the models with cracks, which is calculated using only the first six vibration modes. These modes are identified with the covariance-based subspace identification (SSI) algorithm using the acceleration measurements which are represented by red dots in Figure 12. It is observed that the effect of all three cracks is reflected in the calculated curvature differences, with Cracks 1 and 3 having though a much more pronounced and clear signature, which can be attributed to their location with respect to y axis.

7 | CONCLUSIONS

This paper overviews the establishment of a numerical benchmark for vibration-based monitoring of a small-scale Windspot 3.5-kW WT blade. The numerical benchmark serves as a digital twin to its experimental counterpart on the laboratory-tested small-scale WT blade, which is elaborated upon in the companion paper. The specimen is herein numerically represented by a high-fidelity FE model, which is used to generate the simulated response data for a number of possible damage cases, and environmental as well as operational conditions.

The principal drivers for the development of this numerical benchmark stem from the limitations characterizing the experimental companion work, which are summarized in the following points:

- The experimental test is carried out in parked WT conditions, ignoring thus the effect of operational variability, which constitutes one of the major challenges associated with the vibration-based monitoring of WT blades.
- The experimental investigation of different damage conditions using vibration-based monitoring is always resource-limited and impossible to be quantified.
- The vibration response data of the experimental part are generated by a point load excitation, which can represent only laboratory testing conditions.
- The number and type of vibration measurements in the experimental benchmark are physically limited due to the finite available space on the specimen surface and the limited hardware resources.

As such, the present work emerges from the experimental counterpart as a means of supplementing the latter with a forward simulator, able to (i) account for the effect of operational variability, (ii) enable the numerical investigation of well-defined and quantifiable damage scenarios, (iii) generate vibration response data under realistic loading conditions, and (iv) provide the possibility of extracting sensing information from an extensive multitype grid. In this sense, the simulator can be exploited by the academic and engineering communities, for validation and corroboration of condition assessment algorithms, SHM methods, and system identification tools.

This effort is in analogy to the AIASC-ASCE SHM Benchmark Problem,68,69 which was established in 2004 using simulated and experimental data from a shear frame structure. The case study now pertains to a critical component of wind energy infrastructure, namely, a WT blade. It should be noted that, although the present study is focused on a small-scale blade, the qualitative effect of the challenges and physics to be addressed in an SHM application is similarly scaled to larger WT systems. This however implies by no means that the findings extrapolated from the present study are directly generalizable for larger systems, since damage and aerodynamics are not equally scaled. This case study not only offers the potential to increase the complexity of the investigated model, which now features composite materials and a complex geometry, but further allows to assimilate influence of environmental and operational variability (EOV). The latter is critical in proving efficacy and robustness of SHM and condition monitoring schemes, whose predictive capability might often be limited from the EOV dependance.70

The open-access library is made available under the Sonkyo-Benchmark Github repository, which also serves as the manual. The authors encourage participation by researchers and practicing engineers around the world and would appreciate any comments or suggestions on this work for improving the open-access tool.

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