VRIJE UNIVERSITEIT BRUSSEL

The faculty of Engineering of the Vrije Universiteit Brussel invites you to attend the public defense leading to the degree of

DOCTOR OF ENGINEERING SCIENCES

of **Dominik Fallais**

The public defense will take place on **Tuesday 20th May 2025 at 9am** in room **I.0.02** (Building I, VUB Main Campus)

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PRACTICAL FRONTIERS IN APPLIED MODEL-BASED VIRTUAL STRAIN SENSING FOR OFFSHORE WIND TURBINE SUPPORT STRUCTURES

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Abstract of the PhD research

Offshore wind turbines are typically designed to operate for twenty-five years while being exposed to continuous forces from wind and waves. Over time, the repeated bending of the structure causes small, progressive damage within the material — a phenomenon known as fatigue. Exceeding the materials fatigue capacity eventually will lead to the loss of reliability. Therefore, predicting how the fatigue damage accumulates is an essential aspect of the design process. However, due to inherent limitations and uncertainties in the design process, the fatigue accumulation predicted during the design will differ from the observed accumulation on turbines built according to that design. Monitoring the actual behaviour of the structures at critical locations helps to validate the design and assess the potential for extending the lifetime, but placing sensors in critical locations, such as below the seabed, is often not feasible or too costly.

This thesis explores how to monitor fatigue accumulation without relying on direct measurements at inaccessible locations. Instead, a limited number of measurements from accessible parts of the support structure are combined with detailed computer models which describe the fundamental bending patterns of the structure. This combination allows to estimate the fatigue accumulation at unmeasured locations. This approach is known as model-based virtual sensing.

In this thesis it is demonstrated that improving model fidelity —particularly the modelling of soil-structure interaction — can significantly enhance the accuracy of virtual sensing results. Models based on more recent soil–structure interaction design guidelines (PISA) resulted in notably improved sub-soil fatigue predictions compared to those using older API/DNVGL-based approaches, as confirmed by validation data from multiple turbines. Secondary effects, such as the inclusion of scour protection, led to comparatively smaller improvements. The role of blade flexibility was also examined through virtual sensing; though limited in the studied cases, it is expected to grow in relevance for future turbine generations. Supporting studies included an assessment of corrupted fibre-optic strain data using virtual sensing, and an evaluation of predicted dynamic properties against farm-wide validation data; the latter study also demonstrated that standard design models tend to underestimate key dynamic characteristics, and motivate to further improve physics-based models. Finally, a simplified virtual sensing concept using only a single nacelle-mounted sensor was evaluated through simulations. Results suggest promising potential for minimalistic monitoring setups.

Altogether, this thesis contributes to the practical application of model-based virtual sensing for offshore wind turbine support structures by addressing key challenges in data quality, modelling accuracy, and validation. It demonstrates that, despite inherent limitations, advancements in modelling and sensor strategies significantly enhance the accuracy of virtual sensing for fatigue monitoring—enabling more reliable and cost-effective structural health monitoring, and opening pathways to extend direct monitoring capacity as well as large-scale retrofitting.